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TNO report

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Options to integrate the use of mobile air-conditioning systems and auxiliary heaters into the emission type approval test and the fuel consumption test for passenger cars (M1 vehicles)
Final report

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Summary

Within the framework of monitoring (and steering) the CO_2-emissions of light-duty vehicles their CO_2-emission is measured in the type approval test, according to Directive 80/1268/EEC and subsequent amendments. But in this type approval test only the CO_2-emissions are measured that result from driving the vehicle over the prescribed driving cycle. The fuel consumption and CO_2-emissions due to the use of auxiliary equipment are not (yet) taken into consideration. Two of such sources are the air conditioning and the auxiliary heater that are being installed in more and more cars for the European market in recent years. Reports from both Europe and the USA suggest that the effects of such equipment on the overall fuel consumption and CO_2-emission may be quite significant. For this reason the Commission asked the consultant to start a study into the effects of air conditioning systems and auxiliary heaters on the fuel consumption and CO_2-emissions of passenger cars, and to come with a proposal for a type approval procedure for the measurement of these CO_2-emissions. This study was to be part of a larger study into the contribution to the greenhouse effect of air conditioners. Another study within this same wider context was going to look into the greenhouse effects of the refrigerants used; this latter aspect is therefore emphatically not part of this study!

The present study had the following main objectives:

- To establish, as far as possible, the extent of the additional fuel consumption and resulting CO_2-emission caused by the use of air conditioners and auxiliary heaters in the EU Member States.
- To make proposals for a measuring method for these emissions in a type approval procedure, including cost estimates for possible variants.

As part of the underlying study the magnitude of the effects of air conditioners and auxiliary heaters has been established at an average of 0.28 litre/100 km (7 g/km of CO_2) on an annual bases for Central Europe. For auxiliary heaters the fuel consumption and CO_2-emission are probably in the same order of magnitude or considerably lower, depending on the type of heater used. Based on these figures, the additional fuel consumption and CO_2-emission due to the use of these auxiliaries are significant in relation to the average fuel consumption (6,7 litre/100 km) and CO_2-emission (164 g/km) of the European car fleet. With the fleets CO_2-emission probably dropping to 140 g/km in the next years (driven by the ACEA voluntary agreement), the use of auxiliaries not being taken into account, there is a defined need to control these negative effects on the environment. A way of enabling this control is addressing the emissions and fuel consumption due to the use of air conditioners and auxiliary heaters during type approval. By incorporating this into the type approval procedure the next items could be facilitated:

- The consumer’s right to know and awareness about the additional fuel consumption of his/her vehicle when using auxiliary equipment like air conditioners and heaters
- The possibility for the consumer to identify efficient systems by means of labelling vehicles and systems.
- Encouragement of the industry to develop and market efficient air conditioners and heater

In order to facilitate the items mentioned above, next to establishing the magnitude of the problem, this study evaluated the possibilities for integrating mobile air conditioners and auxiliary heaters in the type approval test for emission and fuel consumption of passenger cars (M1 vehicles).

The most straightforward approach in order to establish the environmental performance of any auxiliary system during type approval would be to perform the fuel consumption test twice: the first time with the auxiliary system switched off and the second time with the auxiliary system switched on under certain conditions. The subtraction of the results of the second and the first test gives the effect of the auxiliary system. This set-up, however, would lead to at least doubling the amount of tests to type approve a vehicle. The financial- and timing implications of such a procedure however would have severe negative effects for the automotive industry.

Taking these implications into consideration, the contractor looked for intelligent options in order to decrease the amount of actual test work, without compromising the basic requires of the procedure. This lead to an approach in which cars types on the market are grouped into certain families, enabling one test set-up per family (instead of one test per type). The basis for this family building process has been similarities between vehicle types. These similarities on vehicle construction level have been split up in 3 groups (subsystems):

- Subsystem I: the power generation system
- Subsystem II: the air conditioner system
- Subsystem III: the vehicle body and its environment

By means of establishing typical parameters for each subsystem (within a certain family) in relation to certain environmental conditions while executing the type approval fuel consumption test on a “parent vehicle”, the actual amount of tests needed to address the topic under investigation can be reduced significantly. In order to live up to the basic requirement of the procedure to be able to rank systems (combinations of the three subsystems) based on their environmental performance, the testing in a climatic camber under stabilised conditions is required.

Because of the relative newness of the subject it was foreseen and accepted that the study would have a largely exploratory character and therefore could not have a fully guaranteed final result, or even a strictly defined ‘path’. It was understood between the Commission and the consultant that the work would have to be carried out in close co-operation and that the direction of progress was likely to be dependent on the findings and discussions during its course. In the course of this process it was agreed that the closer defined purpose of the measuring method mentioned would be that it would allow a system of labelling. To this end a general, although still sufficiently detailed, *approach* for a measurement procedure was developed, but not a fully worked out procedure itself. It was finally agreed that this phase of the programme would result in a report that could serve as a solid basis for a discussion between the Commission and the stakeholders (i.e. the relevant industry and the Member States). The outcome of that process could then serve as the necessary input for the next phase: the detailed development of the actual procedure and its evaluation. This evaluation should contain:

- A check on the practicability of the procedure in the laboratory.
- The exact definition of the requirements for the procedure.
- Insight in the value of parameters and the variability of the values in relation to surrounding conditions.
- Insight in the possibility to use default values for certain parameters based on the knowledge of the variability and the level (of importance) of the parameters.
- A detailed calculation of the actual cost-effectiveness based on actual measured data in a more final procedure set-up. The additional costs for executing the

procedure at this stage is roughly calculated between 0.09 and 14 Euro/vehicle sold, whereas the benefits could not be calculated within the framework of the underlying project because of the large influence of socio/economic parameters on the actual benefits.

This report is laid out as follows:

Chapter 1 details the original considerations of the Commission and the original objectives as outlined in the ‘call for tender’, plus the ultimate objectives as further defined after the first explorations of the field and the first insights into the various possibilities for testing and their consequences both for the costs of testing and the applicability of the test results.

Chapter 2 shortly explores the field and its relevant aspects. In this and most other chapters the main emphasis is on air conditioning systems, either in their own right or as representative for auxiliary systems in general, since they posed the bigger challenge, although auxiliary heaters have been included wherever they present additional or different aspects.

Chapter 3 attempts to roughly determine the extent of the CO_2-problem resulting from the use of air conditioners and the possible magnitude of any improvements resulting from more efficient designs and/or control strategies. Although it proved to be impossible to obtain sufficient real-life data, the exercise, based on (somewhat maximised) estimated data, did show that the magnitude of the effects would indeed be measurable.

Chapter 4 gives a comprehensive overview of existing and short-term future, air conditioning and heater systems. This chapter serves as the basis for the later proposal for a test procedure approach. It outlines the aspects that such a procedure must be able to incorporate and the features that a labelling procedure should aim to incentive and which therefore should have a recognisable effect on the test results.

Chapter 5 outlines what should be considered in a realistic test procedure and gives an overview of how these aspects have been handled in the very few test protocols that do exist or were used elsewhere. The chapter then outlines the requirements for a sensible test method that the consultant regards as essential, and makes proposals for actual values for the test conditions that need to be standardised.

Chapter 6 outlines the proposed approach towards a test procedure that on the one hand needs to take sufficiently account of the existing variation in system variability and vehicle options, and that on the other hand needs to sufficiently prevent the possibility of defeating the basic objective of trustworthy labelling and hence consumer information. The resulting proposal, although seemingly complicated at first sight, was specifically designed to avoid as much as possible any costs that would arise from the necessity to cater for system or vehicle variants, without creating loopholes that might undermine its robustness. This approach was extensively discussed with both the Commission and the industry.

Chapter 7 deals with the limitations of the work done until now, and gives recommendations towards work to be executed in a later phase in order to finalise the procedure.

Chapter 8 finally tries to quantify the costs of the proposed testing against a few simpler but more expensive alternatives. Due to a lack of precise input data this cost evaluation has a somewhat rough character, but it is felt that it can nevertheless serve as an indication of the order of magnitude involved.

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1 Introduction – outline of the problem

Within the framework of monitoring (and steering) the CO_2-emissions of light-duty vehicles their CO_2-emission is measured in the type approval test, according to Directive 80/1268/EEC and subsequent amendments. There are, however, significant sources of CO_2-emission that are not addressed by this test in its current form. Two of such sources are the air conditioning and the auxiliary heater that are being installed in many cars for the European market in recent years. For this reason the Commission has issued a call for tender with the following objectives:

- To get an insight into the extent of this problem
- To receive an overview of existing and possible options to include such CO_2-emission into the (or a) type-approval test
- To receive a development of the option that seems to be most representative for the European situation
- To receive the basic information for a cost-effectiveness study
- To receive concrete proposals with regard to possible amending Directive 80/1268/EEC (fuel consumption) and possibly Directive 70/220/EEC (emissions)

This report describes a programme that was designed to answer these questions in the best possible way, so as to provide the Commission with the tools it needs to close this gap in the monitoring of CO_2 from traffic. It is understood that what the Commission needs is an adequate method to typetest such equipment in an acceptable way to establish their contribution to the overall CO_2-emission of the vehicle in the field. Ideally on the one hand such a method should give adequate insight into the real-world effect of air conditioners and auxiliary heaters; on the other hand the method should be realistic and practical for manufacturers and test laboratories, without undue complications or expensive elaborate test protocols.

A major aspect of this investigation is that it was impossible to foresee at the start of the programme what would be its findings, and therefore what pitfalls there would appear on the road towards a possible typetest procedure. This means that the programme contained an inherent degree of uncertainty and might have to be redirected during its running. To this end a close co-operation with the client was foreseen. At the time of writing the first interim report it was already clear that a major question is the exact purpose of the measuring procedure:

- On the one hand one may want to know the exact increase in greenhouse gas (GHG) emission due to the use of air conditioners and auxiliary heaters, for the purpose of air quality calculations. The catchword here is: ‘emission factor’ and the aim would be knowledge about the extent of the problem.
- On the other hand one may want to obtain a (relative) figure, that in a sufficiently correct way can categorise the GHG effects of air conditioners and auxiliary heaters, so as to serve as a guidance (formalised information) to the buyer, and which would consequently act as an incentive for the manufacturer to develop more efficient systems. The catchword here is ‘labelling’ and the aim would be a decrease of the problem.

As eventually stated by the Commission, the purpose of the present exercise was to be to obtain a better insight into the influence of air conditioning systems and auxiliary heaters on the fuel consumption and CO_2-emission of a passenger car. The purpose of any test procedure that might result from this investigation would be to obtain figures suitable for a labelling system, which would:

- Serve as an incentive for the manufacturer to develop more efficient systems
- Be the answer of the Commission to the customer's 'right to know'

2 The aspects that determine GH-effects

Air conditioner systems obviously are used to cool a car interior under hot ambient conditions. Just as important, however, is their capacity for quick demisting in cold ambient conditions. Some advanced modern air conditioners may function both as a cooler and a heater, whatever is required at the time; they are complete inner climate control systems. Auxiliary heaters may be used to either heat the interior or the engine (coolant or oil). In the latter case they guarantee a quick functioning of the traditional coolant operated heating. Additionally they have a favourable effect on the coldstart emissions. The aspects about air conditioners and auxiliary heaters that determine their GH-effects are the following.

1. <u>The driving energy needed for the air conditioner system</u>. The energy needed to drive the compressor of an air conditioner can amount to several kW. This energy can be delivered in several ways. In practice it takes the form of either mechanical energy or electrical energy. Traditionally this energy is provided by the engine that propels the vehicle. This engine will then have to deliver more power, which results in more emissions, the emission of CO_2 included. In the near future electrical drive may become more popular, with 42 V board systems being laid out for driving several auxiliary systems. One option for such a 42 V board system is to power it by a fully separate fuel cell. In that case the GH-effect would consist of that part of the GHG emissions of this separate board system that can be attributed to the use of the air conditioner system. In the case of a BEV (battery electrical vehicle) the extra GHG emission will take place off-board at the site of the power station.
2. <u>Leakage of the refrigerant</u>. Traditionally air conditioners make use of refrigerants that are potent GHGs. Any possible leakage of these gases, either during operation or at the time of disposal, will contribute to the overall GH-effect of the system. This aspect, important as it is, will not be part of this study; it is the subject of a separate (although related) project.
3. <u>Direct exhaust from an auxiliary heater</u>. When an auxiliary heater is operating with a combustion process (usually fuelled by the fuel that is used to fuel the vehicle’s propulsion engine), there is an additional, usually separate, source of exhaust gases, GHG included. When the auxiliary heater operates electrically the situation as described under ‘1’ applies.

The actual amount of GHG caused by an air conditioner is determined by the following characteristics:

a) <u>The capacity of the air conditioner system and the efficiency of its drive</u>. Obviously the GH-effect of an air conditioner is directly determined by the amount of energy needed to drive the system. This mainly involves driving the compressor, which may be done either mechanically or electrically. Additionally a couple of fans has to be driven, that blow air over a pair of heat exchangers. As a rule these fans are driven electrically, since they require much less energy than the compressor. This aspect is fully determined by the design of the system, and consequently could, at least in theory, be determined in isolation.

b) <u>The control approach of the air conditioner system capacity.</u> In its most primitive form the system can only be switched on or off. When in use it is always operating at full capacity and the cooling performance can only be regulated by tempering this performance through the additional use of the heater. Also the actual power consumption further increases by the fact that the compressor drive is rigidly linked to the engine, causing the compressor unnecessarily to speed up with increasing engine speed, whereas its capacity has by necessity been laid out for low speed performance (the system still has to function in an adequate manner even at low speeds and idle). Early systems all operated in this way, but by now their popularity is decreasing. Modern systems are capable to adjust the compressor activity (and hence its energy demand) to the demand for cool air. Even more advanced compressor systems operate at a (more) constant speed, especially when driven electrically; this does greatly reduce the power demand when the system operates at part load. The consequence is that the GH-effect in the field is very much dependant on the actual way part load of the system is achieved; any determination of the full load power demand only may lead to a misleading ranking of systems. This links the GH-effect to the operating conditions of the system (such as the actual degree of cooling required).

c) The efficiency with which the drive energy is generated. At this moment the vehicle's propulsion engine is used to generate the drive energy for the air conditioner system. The efficiency with which the engine does so is variable. At times when the engine, due to its vehicle propulsion task, is operating in an efficient area of its operating map, the air conditioner drive energy will also be generated in an efficient way. But when the engine is operating in part load or at idle, usually inefficient operating conditions, the extra energy needed to drive the air conditioner is also generated in a less efficient way. On the other hand at low engine load the drive energy of the air conditioner adds a significant extra engine load, which tends to shift the engine into a more efficient part of its operating map. Furthermore mechanical energy may be generated more efficiently than electrical energy (which requires an extra conversion step), although a separate fuel cell operated 42 V board system may present yet another picture. A different, but equally important, aspect is that when a vehicle is fitted with a start-stop system, that switches off the engine when the vehicle is not moving, the use of an air conditioner will prevent stopping the engine under those conditions, thereby significantly increasing the GH-effect, since in that case all the engine's mechanical losses are attributable to the use of the air conditioner. These considerations mean that the effect of the air conditioner system on the generation of GHGs in practice is usually closely linked to the operational pattern of the vehicle at the time of use. Only in the case of a full electrical drive *and* a completely separate system for electricity generation (either a stand-alone fuel cell driven 42 V board system, or an off-board electricity source) would the GH-effect be unrelated to the pattern of use of the vehicle.

d) The demand for cool air. This in turn is dependent on two different things:

- *The climatological situation.* It will be obvious that the demand for cooling is to a great extent determined by the climatological situation in the field. This means that the GH-effect is differing over Europe, depending on the regional climatic zone, with temperature and sun radiation as the main variables.
- *Conditions of use.* The actual ambient conditions during the use of the system can still vary, even within a given climatic zone, depending on the time of the year, and the time of the day, when the trip is made. At the end of the next section it will be shown that this is in fact one of the biggest single influence factors.
- *The design of the vehicle.* It is the design of the vehicle (total glass area, angle of windows, tinted glass or not, even the colour of the body) that determines what the demand for cool air actually is under any given climatological situation. This means that the performance demand of the air conditioner is dependent on the vehicle design and even to some extent on the actual vehicle.

The actual amount of GHG emissions caused by heaters can be determined using more or less the same basic characterisation as used for air conditioners. Differences with air conditioners in how these characteristics affect the amount of GHG can be found in:

- The energy supply to the system; fuel fired heaters, for example, do use fuel directly from the vehicles fuel tank instead of mechanical energy form the engine.
- The control strategy, simply because heaters interact with the engine coolants temperature.
- The efficiency of the system, because fuel fired heaters do not use this mechanical energy.
- The fact that for heaters the demand for **warm** air determines the amount of GHG.

3 Extent of the current GH-effect

As stated by the Commission, the purpose of the present exercise is to obtain a better insight into the influence of air conditioning systems and auxiliary heaters on the fuel consumption and CO_2-emission of a passenger car. To this end a first exploration of the possible global effect was made. During the running of project and at several meetings with representatives from the industry it was repeatedly stated by this industry, however, that they did not possess the data necessary for a calculation that in any way would approach the actual situation in the field. Therefore, to obtain a sufficient feeling for the possible extent of the problem, and with that a first idea as to whether there might be a problem at all, a tentative calculation was made. This calculation, although based on the consultant's expert judgement and relevant experience, should therefore be regarded as mainly a rough exploration of the field, without any claim as to real-world accuracy. Its main outcome would be to give an idea if the effects are likely to be measurable.

3.1 Global calculation

First a global calculation has been made. The input variables needed for a detailed estimate would be:

- The penetration of air conditioner systems into the European car fleet.
- The division of this penetration over petrol and diesel cars
- The general nature of the systems already in the fleet (i.e. the relative shares of unregulated on-off systems and more advanced controlled systems).
- The coefficients of use (i.e. the percentage of 'on'-time, and/or the degree of part load for controlled systems) for the average vehicle in different climatic zones.
- The power demand of the different systems and its GH-effects as a function of the coefficients of use for the average operational conditions of a vehicle.
- The distribution of the different climatic zones over Europe.

The above mentioned input variables are also required for a global calculation for auxiliary heaters.

Since the exact information, needed to produce an accurate calculation, is still largely lacking (which is the very reason for the present investigation), a more simple approach has been chosen, aiming at the determination of an order of magnitude of the effect.

When the total additional FC and CO_2-emissions due to air conditioner use are to be estimated, above all three aspects have to be considered:

1. The first aspect is the load applied by the (conventional) air conditioner to the vehicle's engine. This load basically consists of a mechanical load applied by the compressor directly to the vehicle's engine and an electrical load applied by the electrically propelled fans, applied indirectly to the vehicle's engine, via the battery and generator system. This load is dependent on many factors, but in order to arrive at a relatively easy method of calculation it is assumed that the ambient temperature is the most important factor here.
2. The second aspect is the efficiency of the vehicle's engine, which is not constant. It is well known that the efficiency of an internal combustion engine varies with its load and also its speed, and thus according to the driving circumstances. Hence the

efficiency at which the engine generates the power required for the air conditioner system varies with the use of the vehicle.

3. Finally there is the influence of the mass of an air conditioner system that has to be added to the vehicle mass. Additional engine power is required to accelerate this mass during vehicle operation. This additional engine load leads to additional fuel consumption and additional CO_2 emission.

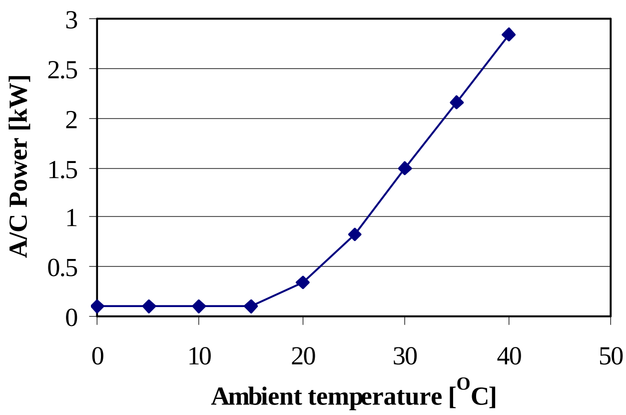
Since the purpose of this exercise is only to give an indication of the level of the additional FC and CO_2-emission, a simplified model calculation is used, based on the data and insights gained during only a few air conditioner studies (ADEME, TNO, VALEO).

An additional effect would be that the air conditioner of a car just started, first has to cool down the interior, whereas after an initial phase the air conditioner only needs to stabilise the temperature. This means that the average trip length has an influence on the total extra fuel consumed and CO_2 emitted. In the following calculation this influence has been neglected.

The power needed to drive the air conditioner

From the available data a rough function can be made describing the required air conditioner power of currently available air conditioners as a function of the ambient temperature. This can then be combined with information concerning the average daytime temperature for different regions of Europe.

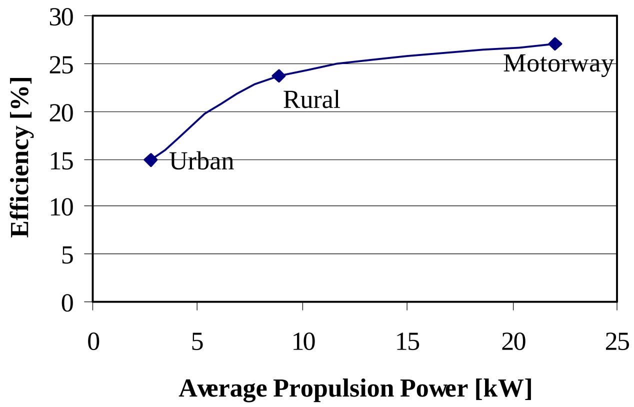
Figure 1: required power for an air conditioner versus ambient temperature.



The average efficiency of the power generation

Next the efficiency at which the power is generated by the vehicle's engine has to be estimated. As was stated before, this efficiency varies with the engine load and thus with the driving situation, and even with the additional load applied by the air conditioner. In the next figure an example is given for the efficiency of an 'average' conventional powertrain over three typical driving situations, with increasing average driving power: urban, rural and motorway driving respectively.

Figure 2: Estimated powertrain efficiency versus average required propulsion power.



With an assumed mileage distribution over the three driving situations according to 0.3/0.4/0.3 the average efficiency for a powertrain with a petrol-fuelled engine is approximately 18%. For diesel this is approximately 22%. The relative shares of petrol and diesel cars have been assumed to be 0.65/0.35 for all regions.

So for every kilowatt to drive the air conditioner, 4.5 to 5.5 kW is required from the fuel (diesel and petrol receptively). This equals approximately 0.62 litres of fuel per hour for petrol engines and 0.45 litres of fuel per hour for diesel engines. For an average European car driving at an average driving speed of 40 km/h (as on example) the additional FC is approximately 1.55 litre/100km per kW of A/C power for petrol engines and 1.13 litre/100 km per kW for diesel engines. At an assumed distribution of petrol and diesel passenger cars of 65 and 35% respectively the additional FC is 1.4 litre/100km per kW for an average passenger car.

The influence of the additional mass

For the calculation of the additional FC due to the air conditioner mass the TNO emission model VERSIT has been used. For an average petrol fuelled vehicle the additional FC is 0.05 litre/100km per 10kg. For an average diesel fuelled vehicle this is 0.03 litre/100km per 10kg. Given the approximate character of the calculations and the small percentage this would add to the 1.4 litre/100 km for the operation of the vehicle.

The additional FC per kilowatt of air conditioner input power and the defined relation between ambient temperature and air conditioner power are used to determine the FC at different ambient temperature ranges and weighted according to their distribution. This was done for three different European regions separately.

In the following table the results are given, taking the daily temperature distribution per European region into account.

Table 1: The additional life-cycle FC for three typical European regions, taking the daily temperature distribution into account.

Temp.	24h temperature distribution			Add. FC	Weighted additional FC		
	Northern Europe	Central Europe	Southern Europe	[l/100km]	Northern Europe	Central Europe	Southern Europe
[^{O}C]	[%]	[%]	[%]		[l/100km]	[l/100km]	[l/100km]
<15	85	74	50	0.14	0.12	0.10	0.07
15..20	9	12	17	0.14	0.01	0.02	0.02
20..25	4	8	15	0.21	0.01	0.02	0.03
25..30	2	4	13	1.15	0.02	0.05	0.15
30..35	0	1	4	2.09	0.00	0.02	0.08
>35	0	1	1	3.02	0.00	0.03	0.03
Sum	100	100	100		0.16	0.23	0.39
Add. mass					0.05	0.05	0.05
Total					0.21	0.28	0.44

From this table can be concluded that the average annual additional FC of a vehicle with an air conditioner amounts 0,28 l/100 km for Central Europe and ranges from 0,21 l/100 km for the Northern European region to 0,44 l/100 km for the Southern European region.

Regarding the additional CO_2-emission, the FC values [l/100km] can be converted directly to CO_2 emission values [g/km] since the CO_2-emission is almost directly proportional to the FC. This results in the following additional CO_2 emission: 5 g/km for Northern Europe, 7 g/km for Central Europe and 11 g/km for Southern Europe.

In relation to the average fuel consumption (6,7 litre/100 km) and CO_2 emission (164 g/km) of the European new car fleet (ACEA, 2002) these additional FC and CO_2 emissions can be regarded as significant, and range from 3,1% for Northern Europe and 4,2% for Central Europe to 6,6% for Southern Europe.

The above conclusion is valid for the average European car. Per country the situation can be significantly different, not only for climatic reasons, but also because several other assumptions (distribution of mileage over road types, average speeds, distribution petrol/diesel, etc.) in practice are very country dependent.

Heaters

Next to the mobile air conditioners, auxiliary heaters are also suspected to contribute significantly to the FC. In this paragraph a calculation will be made on the effect of the use of auxiliary heaters on FC and CO_2-emission. The calculation of the additional FC by the use of auxiliary heaters, however, lacks even more input data than the calculation for the air conditioners. In the context of this report it should be considered that an indicative result of the calculation will suffice in order to gain insight in the order of magnitude of the effect, next to the effect calculated for mobile air conditioner systems.

For the calculation a distinction should be made between two different systems because both systems do affect the FC in a different way, as will be described later on in paragraph 4.2:

1. Fuel fired heating systems.
2. Electrically powered heating systems using PTC-thermistors.

System 1 is basically a stand-alone system that uses mainly fuel from the fuel tank for the burner, besides some minor amount of electrical power for operating the fans.
System 2 uses electrical energy from the vehicles electrical system (generator, battery).

The systems are used to either heat up the engine coolant or to heat up the cabin directly by heating up a forced airflow that is directed into the cabin. The first option comes with the merit that the engine is warmed up quicker. Thus, eventually, less fuel is consumed due to an improved efficiency of a warm engine compared to a cold engine.

Fuel fired heater
In the literature [Hammerschmid, Webasto] FC figures were found for typical automotive fuel fired heaters. The capacity of these heaters ranges from approximately 0.9 to 5kW. The fuel consumption of these heaters ranges from 0.11 kg/h to 0.54 kg/h (diesel). The efficiency of a fuel-fired heater is about 85%.

In the same literature an example with a vehicle in the ‘limousine range’ showed that a heat up time of 30 minutes was required to raise the cabin temperature from -5^{O}C to “comfortable warm” with a fuel fired heater operating at 5kW. This heater consumes about 0.54 kg of fuel per hour. For a 30 minutes heating up period this equals 0.27 kg of diesel or 0.33 litres of diesel. For a vehicle of the size of an average passenger car the FC would be less and in the order of 0.2 litres due to a smaller interior volume.
For a higher ambient temperatures the amount of fuel consumed would be less because the time to heat up to a comfortable temperature is shorter.
The figure might be offset by the fact that heaters of another capacity may be used with engines with another level of thermal efficiency: the thermal efficiency of the engine namely determines how much waste heat is available for heating and thus what capacity is required for the heater.
Besides the FC of the heater system itself, the weight of a fuel-fired heater causes additional FC. The weight range of the given Webasto systems is 2.9 kg for the 1 – 2kW heaters to 5.9 kg for the 5kW heaters. At 0.05 l/100km/10kg this means an additional FC in the order of 0.015 to 0.03 l/100km, depending on the weight of the system.

Electrically powered heating system with PTC-thermistors.
A typical automotive heating system with PTC thermistors has a heating capacity in the range of 1 – 2kW [Amsel, 2001]. The PTC unit is normally split up into 3 to 5 smaller elements of 300 to 400W. The elements can be controlled separately. Systems with a PTC-unit are very demanding concerning their power need from the electrical system. Today’s electrical systems often lack power when the installed heating capacity would be fully demanded at low ambient temperatures. [Amsel] shows some power consumption figures over the European Driving Cycle: with a 120A alternator system 594W of electrical power is consumed on average over the driving cycle. With the same PTC-unit but with a 150A alternator system the average electrical power consumption

by the PTC-unit is about 33% higher, meaning that more power was left from the electrical system for heating.
For the calculation of the additional fuel consumption due to the electrical power consumption the consumption figure of 1.4 l/100km per kW of engine power for propelling the air conditioner compressor can be adapted within the calculation. The only difference with the air conditioner system is that the energy is now supplied indirectly by the engine through the generator/battery system instead of directly by the engine. The efficiency of a generator is approximately 60%. This results in an additional fuel consumption of 2.3 l/100km per kW of electrical power required for the PTC-unit (with fans).

The heating systems will only operate under full load conditions during warm up of the cabin from low ambient temperatures to a desired comfortable cabin temperature. From the available data it could not be derived how long this period takes for a given ambient temperature. From the available data it also could not be derived how much heat is required to maintain the desired cabin temperature from the moment this temperature is reached. The consultant feels that today’s vehicles equipped with highly efficient engines will probably still be able to supply enough heat to maintain the desired cabin temperature after warming up at a moderate ambient temperature. But at which ambient temperature additional heating is required from an auxiliary heating system just to maintain the desired temperature is not known. In general more information is needed on the relation between heating power and ambient temperature.
Besides this information, just like the calculation for air conditioners, more information is required on the use of heaters, see at the first bullets of this paragraph.

For the fuel-fired heater it can be concluded that even under full load conditions this system consumes far less energy than an air conditioner under full load. The electrical heater with PTC-units operating under full load, however, consumes an amount of energy that is in the order of magnitude of the energy consumption of an air conditioner, but still less than the energy consumption of an air conditioner. It is not known to what extend an electrical heater contributes to the energy consumption under a load condition at which the temperature of the cabin is stabilised at the desired comfortable temperature, at a given ambient temperature.

The effects of the described systems on fuel consumption are not captured within the current type approval test. However, heating systems may be captured, partly, in the $-7^{O}C$ test. This is due to the fact that some systems automatically switch on as the result of a demand for heat from the engine and not from the driver (cabin heating is switched off during this test).

3.2 Sensitivity analysis

For the results of the calculation above, a range of uncertainty should be given. An error analysis throughout the calculation is not possible because no exact figures are available on the errors of each parameter within the calculation. Therefore a sensitivity analysis was performed. In this analysis the variance of each parameter is assumed in such a way that this variance might very well lie within the range the actual error lies in.

The following parameters within the calculation are subject to uncertainty.

Air conditioner power as a function of temperature

For this function an uncertainty range of 15% is assumed. This range should cover the uncertainty of the average power that is required for the air conditioner to operate at a certain temperature and level of solar radiation, for all vehicles with an air conditioner.

Powertrain efficiency

For the powertrain efficiency a relative uncertainty of 10% is assumed. This range should cover the uncertainty of the average powertrain efficiency of a fleet of passenger cars that is representative for Europe, under three specific driving situations, using diesel and petrol fuelled engines.

Distribution over the three driving situations

For the distribution over the three driving situations a variation on the average distribution should be used, because the distribution of the vehicle kilometres travelled over the three driving situations urban/rural/motorway, is subject to a certain amount of uncertainty. The two distributions that are used to describe the uncertainty range of the distribution in a positive and negative direction, considering the influence on the final result of the calculation, are 0,2/0,3/0,5 (sales representative doing much of his travels on a motorway) and 0,5/0,3/0,2 (taxi, or delivery vehicle) respectively.

Fuel type distribution

As for the distribution over the three driving situations: an error on the given distribution over the fuel types petrol and diesel should be covered by a range of uncertainty. The two distributions that are used to describe the uncertainty range of the distribution over petrol/diesel, are 0,5/0,5 and 0,75/0,25 respectively.

Ambient temperature distribution

The temperature distribution that is used in the calculation is a daily (24-hour) temperature distribution. It is obvious that most of the vehicle kilometres are travelled by day. When 24 hour temperature profiles are analysed for North, Central and South Europe it can be concluded that vehicle operation mainly in the daytime would lead to an increase of the ambient temperature the vehicles are operated under, compared to the calculated situation. This increase amounts approximately 3^0 C and depends very much on the local climate. This increase is adapted within the sensitivity analysis.

In the table below the results are given of the sensitivity analysis in which the above mentioned ranges of uncertainty are processed.

Table 2: The sensitivity of the calculated additional FC, due to assumed ranges of uncertainty of parameters within the calculation.

	Northern Europe	Central Europe	Southern Europe
	[l/100km]	[l/100km]	[l/100km]
Average	0.16	0.23	0.39
Min.	0.11	0.16	0.26
Max.	0.26	0.41	0.75

In the table above the values for the upper range deviate more from the average values than the values for the lower range. This is caused by the temperature distribution, which has been assumed to deviate upwards only.

The conclusion can be that, with exception of the temperature distribution, even the assumption of rather large uncertainties does not result in a bigger margin than about 1/3 of the calculated value. On the other hand a rather large uncertainty originates from the assumed temperature, that furthermore increases for the higher temperature climatic zones, amounting to additional consumption effects in the order of 30 %, 45 % and 60 % of the calculated values respectively. Ironically the daily temperature profiles of these zones are the most accurately established data. The uncertainty does, however, stem from the uncertainties about the exact profile of use: how many kilometres during exactly what part of the day (and consequently: during what ambient temperatures). The most obvious conclusion of this analysis must therefore be that for a good inventory much more must be known about the exact usage profile.

3.3 Possible magnitude of the effects: computer simulation

By way of a check on the validity of the assumed operational parameters, the possible magnitude of the influence of certain design and control parameters a computer simulation was executed. This simulation programme was carried out with the TNO simulation model ADVANCE [Eelkema et al.]. The principle of this model relies on the calculation of the fuel consumption second by second, giving the fuel consumption accumulated per part of a driving cycle. The actual road load figures, the air conditioners power demand and an engines fuel efficiency map are the input parameters for the model. For the simulation the engine map and the road load figures of a typical average European petrol fuelled passenger car were used. A total of 4 situations were simulated in order to determine:

- Whether the influence of an air conditioner on the FC of a passenger car is measurable.
- Whether a more intelligent air conditioner control would lead to a significant reduction in energy consumption.
- Whether a more efficient air conditioner system layout would lead to a significant reduction in energy consumption.

The 4 situations are specified as follows:

1. The European Driving Cycle with the air conditioner turned off (reference).
2. The European Driving Cycle with the air conditioner turned on. The air conditioner is assumed to be a manually controlled one. The compressor’s power demand is assumed to be 4 kW constant over the complete driving cycle. (high power demand, no intelligent control)
3. The European Driving Cycle with the air conditioner turned on. The air conditioner is assumed to be an automatically controlled one. The compressor’s power demand is assumed to be constant 4 kW over the first half of the Urban Driving Cycle (6,5 minutes) and constant 1,3 kW over the second half of the Urban driving cycle and the Extra-Urban Driving Cycle (high power demand and intelligent control).
4. The European Driving Cycle with the air conditioner turned on. The air conditioner is assumed to be an automatically controlled one. The compressor’s power demand is assumed to be 3 kW over the first half of the Urban Driving Cycle and 1 kW over the second half of the Urban driving cycle and the Extra-Urban Driving Cycle. This situation was introduced for comparison reasons; in order to show the effect of the application of a system with an improved efficiency (+25%). (decreased power demand and intelligent control)

Figure 3: compressor load during the European Driving Cycle for the 4 specific situations.

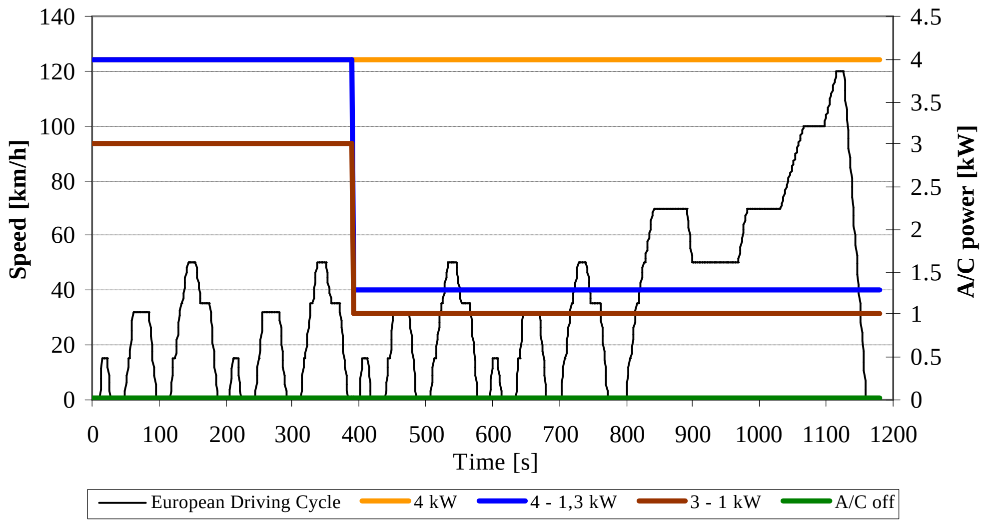
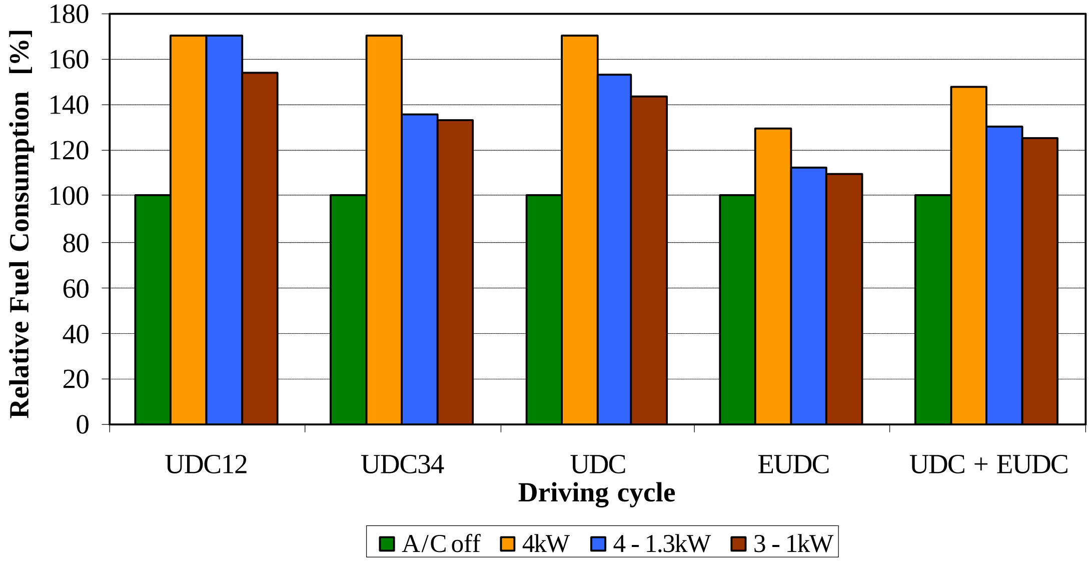


Figure 4: The fuel consumption under 4 specific compressor load situations, relative to the 'A/C off' situation (UDC12 = first half of the UDC, UDC34 = the second half of the UDC).



In the figure the following results are presented:

Table 3: The fuel consumption over the FC-test of an average petrol passenger car under 4 specific compressor load situations.

Fuel consumption [l/100 km]	UDC12 (first half of the UDC)	UDC34 (second half of the UDC)	UDC	EUDC	UDC + EUDC
A/C off	7.97	7.97	7.97	5.53	6.43
4kW	13.61	13.61	13.61	7.16	9.54
4 - 1.3kW	13.61	10.83	12.22	6.20	8.42
3 - 1kW	12.31	10.60	11.46	6.07	8.05

Table 4: The fuel consumption over the FC-test under 4 specific assumed compressor load situations, relative to the 'A/C off' situation.

Relative to A/C off [%]	UDC12	UDC34	UDC	EUDC	UDC + EUDC
A/C off	100	100	100	100	100
4kW	171	171	171	129	148
4 - 1.3kW	171	136	153	112	131
3 - 1kW	154	133	144	110	125

The figures show that "state of art" air conditioner systems can result in improvements in fuel consumption. Intelligent air conditioner control could result in a decrease in FC in the order of 17% for an individual car. More efficient air conditioners set-ups could result in a decrease of FC of about 6% compared to the reference system. The overall effect of stimulating intelligent and economic systems could therefore result in a reduction in FC of about 23%.

These figures are calculated for a petrol vehicle that has the air conditioner switched on all the time: the air conditioner has to cool the cabin during the full test. When the annual use under real world conditions is considered, the effect of an improvement on the systems efficiency will of course be less than pointed out in the text above.

The tables and the figure above clearly show the impact of the use of an air conditioner on the fuel consumption over the European Driving Cycle. This means that a possible test procedure using this driving cycle will certainly give meaningful and measurable results concerning the additional fuel consumption of air conditioners.

From the results of these computer simulations it could be deduced that the engine efficiency is significantly affected by the extra load of the compressor drive, which moves the engine into a higher efficiency part of its operating map. This effect was not incorporated into the calculations shown in subparagraph 3.1. Consequently the results presented in subparagraph 3.1 could be argued to be on the pessimistic side. On the other hand the sensitivity analysis has shown that the uncertainties, especially concerning the conditions of use, are so big that at this moment no more exact figures can be given.

4 Overview of the possible systems

The following paragraph gives an overview of the systems currently on the market, or expected on the market between now and the midterm future.

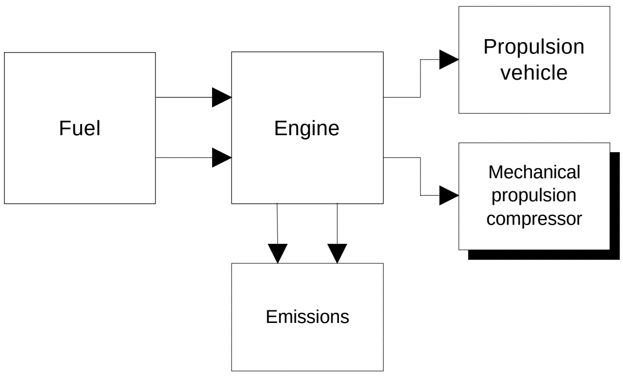
4.1 Air conditioners

4.1.1 The powering of the system

An in-vehicle air conditioning system does not operate stand-alone, but depends on the power-supply from a vehicle related power source. At this moment, for most vehicles, it is the vehicle's engine that is used to drive the compressor of a conventional air conditioning system. In such a case the operating power of an air conditioning directly affects the fuel consumption (FC) and emissions. Apart from the quality and set-up of the system itself, the vehicle's engine, body and interior have a clear influence on the additional amount of fuel consumed by the use of an air conditioning system. Because of the aforementioned reasons the air conditioning system will not be dealt with in isolation. The possible integration of the air conditioning into the powertrain, the vehicle's body and the interior configurations influencing the operating conditions of the air conditioning will be discussed as well.

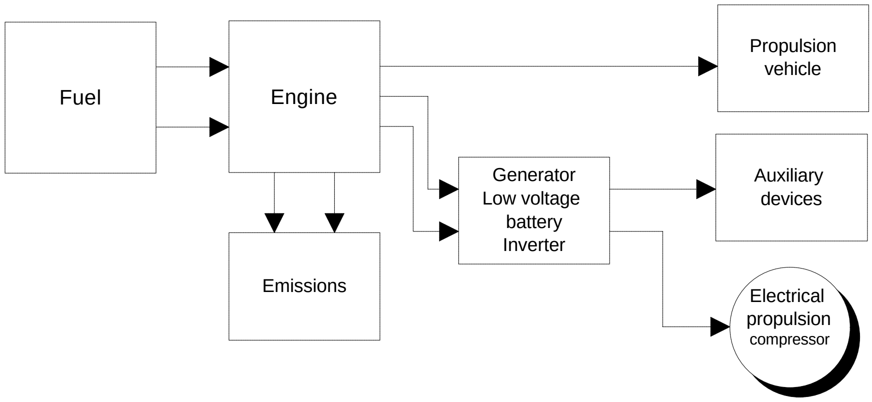
The most common configuration of an air conditioning system integrated into a vehicle is the one with a conventional powertrain, with an internal combustion engine (otto or diesel) propelling the air conditioning compressor mechanically.

Figure 5: A conventional powertrain with an internal combustion engine driving the air conditioning compressor.



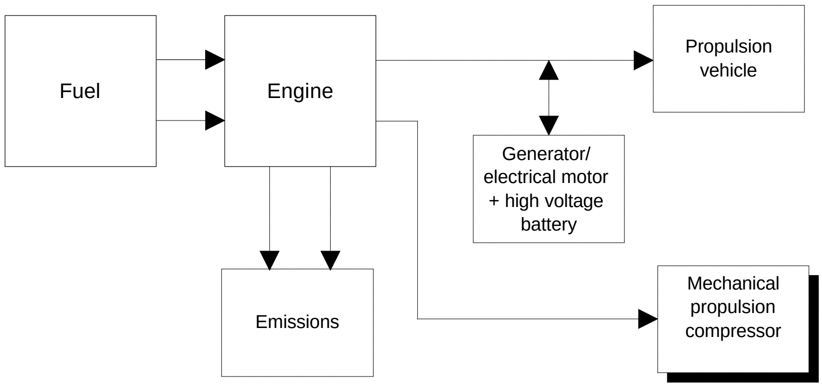
The air conditioning compressor can also be driven by an electric motor, as is shown in the next figure. The configuration given has consequences for the demand of extra engine load due to the use of the air conditioning. This demand is no longer directly linked to the engine anymore because the battery, generator and inverter interfere at this point. It is mainly the battery that might influence the relation between air conditioning power demand and engine power supply because the battery functions as energy buffer. Furthermore the efficiency of the electric system differs from the efficiency of the conventional, mechanical, drive of the air conditioning compressor. The electric drive of the compressor does; however, come with the merit that the air conditioning load can be controlled more accurately by the possibility to vary the compressor's speed independent from the engine's speed.

Figure 6: A conventional powertrain with an internal combustion engine, the air conditioning compressor is driven electrically.



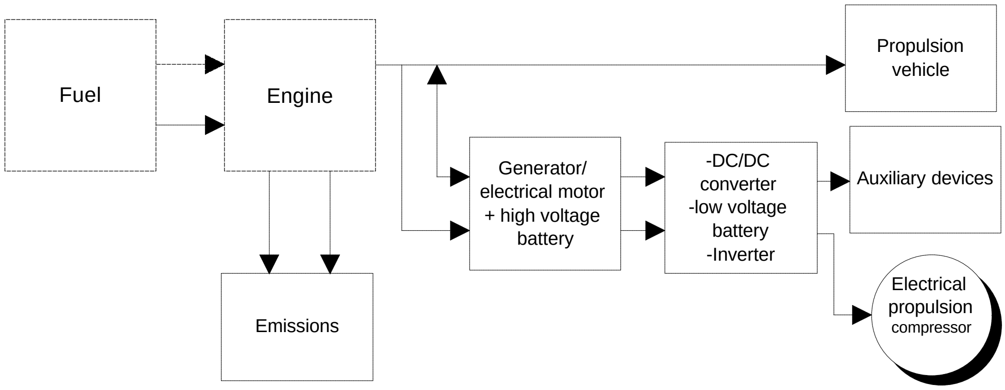
The integration of the air conditioning system in a hybrid or mild hybrid vehicle with an air conditioning system (Toyota Prius, Honda Insight) is often configured as shown in the figure below. The air conditioning compressor is driven mechanically by the vehicle's engine as in a conventional powertrain. This configuration has consequences, however, for the merit that a typical hybrid powertrain brings about. Hybrid vehicles commonly have a start-stop control strategy for the engine in order to save fuel: when the vehicle decelerates or stops the engine is turned off (only when the high voltage battery is not fully depleted). When the air conditioning is switched on, the engine cannot be stopped because the air conditioning needs mechanical power from the engine to operate.

Figure 7: A hybrid powertrain with mechanical propulsion of the air conditioning compressor by the engine.



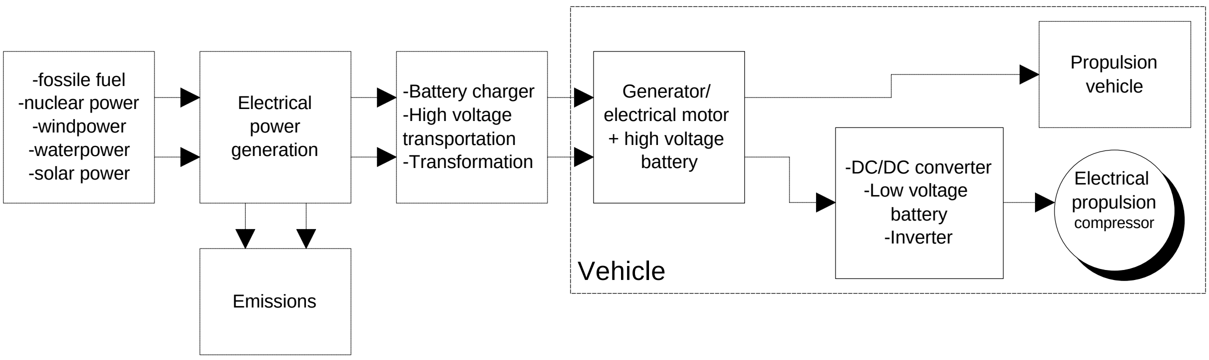
In the next figure a configuration of a hybrid powertrain is given with the air conditioning compressor driven by an electric motor. In contrast to the system with mechanical propulsion of the air conditioning compressor this configuration allows the

Figure 8: A hybrid powertrain with electrical propulsion of the A/C-compressor.



A fully electric powertrain (BEV = battery electric vehicle), as shown in the next figure, requires electrical propulsion of the air conditioning compressor. In contrast to all the aforementioned configurations the extra energy consumption and emissions do not take place directly at the vehicle, but at the power plant that generates the electric energy (in fact the electric energy is produced from a mixture of energy supplied by gas, coal, oil and nuclear plants and by solar, wind and waterpower).

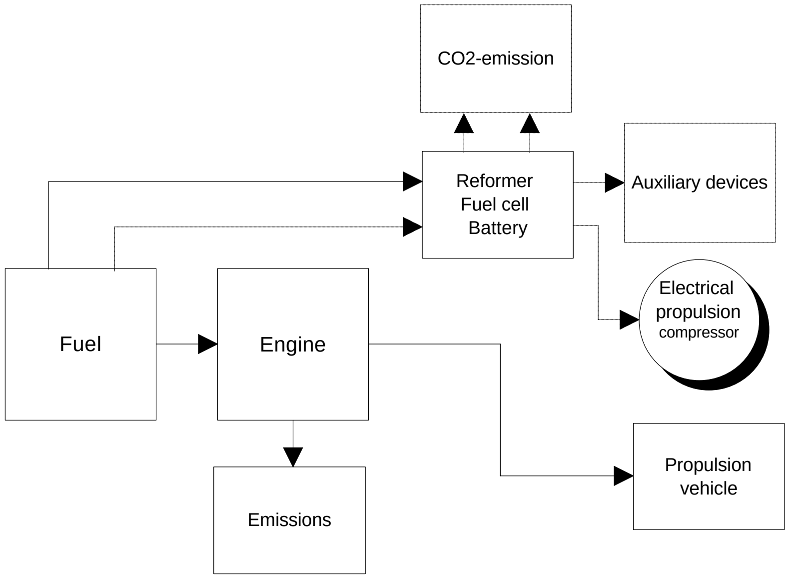
Figure 9: A fully electric powertrain, together with the path for production and transportation of electricity.



Additionally to the powertrain configurations described above, the fuel cell vehicle has to be mentioned as a future option. A fuel cell vehicle will have electrical propulsion of the air conditioning compressor. On this type of powertrain the electrical power is generated in the fuel cell. The fuel cell in turn can be fuelled directly by pure hydrogen stored in the tank of the vehicle, or by a reformed fuel. It is clear that for this type of powertrain the additional load by an air conditioning system will also influence the load of the system and will lead to additional consumption of energy and additional emission of CO_2.

Another possibility is using a fuel cell as an auxiliary power unit, as is shown in Figure 10. The electrical power generated by the fuel cell can be used for the electrical propulsion of the air conditioning compressor, the air conditioning fans and other auxiliary devices. This method of electric power generation also comes with the fact that an additional amount of fuel will be consumed and an additional amount of CO_2 will be emitted when the air conditioning system is working.

Figure 10: A conventional powertrain with a fuel cell as auxiliary power unit.



4.1.2 *The system itself*

For the in-vehicle air conditioning system there are some variations in the way the system is configured. This paragraph will deal with the basic operation principles and with possible configurations for early and current air conditioning systems. Additionally some information will be given on recent developments on in-vehicle air conditioning systems.

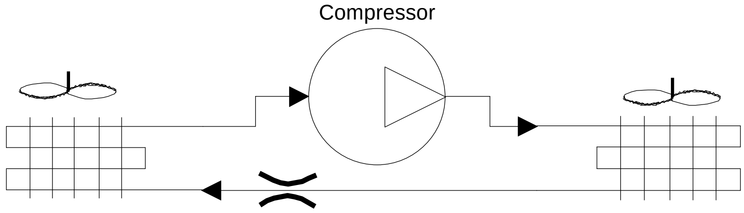
Today, all A/C systems work according to a thermodynamic process operating with a compression/expansion cycle. In this cycle, a gas with suitable thermodynamic properties is circulated in a closed loop system and changing phase between gas and liquid. The basic configuration of such a system consists of 4 specific parts:

- a compressor for the compression of a gaseous substance
- a condenser for the release of the compression heat from the compressed substance and to condense the gas into a liquid
- an expander for the expansion of the compressed substance; originally this was just a throttling orifice
- an evaporator that evaporates the expanded and hence cooled down substance.

The evaporator and condenser are in fact heat exchangers. A forced airflow is directed past both in order to respectively supply the ventilation air that has to be cooled to the evaporator and to carry away heat from the condenser.

More in detail the basic function is as follows:

Figure 11: The basic set-up of an air conditioning system.



In the evaporator the liquid refrigerant is boiling at the low pressure inside. The evaporation heat needed to turn the liquid into a gas is taken from the hot and often humid air that the blower is forcing past the evaporator core. In order to have a heat flow from the air to the refrigerant, the refrigerant temperature has to be lower than that of the air. This low evaporating temperature is obtained by running the evaporator at the low inside pressure mentioned. Since the boiling refrigerant extracts its evaporation heat from the air, the air turns cold. If the air is chilled below its dew point, water is also extracted from the air. This cold and dehumidified air is then distributed into the vehicles passenger compartment.

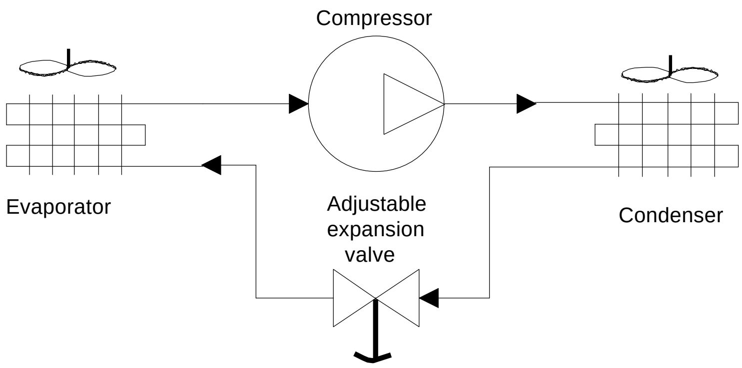
The task of the condenser is to dissipate the heat that the refrigerant has absorbed. In order to be able to do so the gas has to be at a higher temperature than the air that flows past the condenser. This is accomplished by compressing the refrigerant to a sufficiently high pressure and thereby to a temperature that is above that of the ambient air flowing past the condenser.

Energy is needed to drive the compressor and this can be expressed as the power taken from the vehicles engine. By far the most common type of transmission for this is through a belt drive between the crankshaft of the engine and the compressor. This inflow of energy, resulting in higher pressure and temperature, is added to the energy that was already absorbed in the evaporator, and the sum of these two is what the condenser has to lose to the cooling airflow.
During this process the refrigerant turns from a gas back to a liquid: it condenses.

This liquid refrigerant, at the high condensing pressure, now has to be brought back to the lower evaporating pressure before returning to the evaporator. This is done in the so-called *throttling* device, often called the *flow control* device because the function of this component is also to control the amount of refrigerant that is circulating through the system, depending on the heat-load on the evaporator

The two dominant types of throttling/flow control devices on the market are the *orifice tube* and *TXV* (Thermostatic eXpansion Valve). In an orifice tube system, capacity control/freeze protection is carried out either by a pressure switch or by a pressure transducer sensing the evaporation pressure as close as possible to the evaporator outlet. Freeze protection means that the temperature of the evaporator is not allowed to fall below 0 º C for any length of time. If, as described above, water is condensed out of the airflow, this water would freeze and eventually block the airflow if the evaporator was allowed to operate at too low a temperature. And thermodynamics tell you that for a boiling liquid pressure and temperature are rigidly linked. Actually, in practice capacity control and freeze protection is the same thing. Despite the name, the TXV has no thermostatic function. For a fixed displacement/cycling clutch compressor system, capacity control/freeze protection in a TXV-system is performed by a temperature sensor located either in the airflow immediately after the evaporator or mounted into the evaporator core.

Figure 12: A basic air conditioning system with an adjustable expansion valve for the regulation of the pressure to the evaporator.



From the basic A/C-system described above several variations are possible. A major aspect influencing the chosen set-up is the way in which the demand for cold air is achieved by the control of the system.

Historically the basic AC system has been designed to cool down the air to a fixed, low temperature under all circumstances (=fixed setpoint). If this temperature resulted in a too cold passenger compartment, either the driver (manual system), or the system itself (automatic system) applied partial reheating by the heater core in the climate unit. This type of climate control is often referred to as *cool down and reheat*. For some specific conditions it offers very important and valuable benefits but for all other conditions it is a waste of energy. The conditions where the 'cool down and reheat' strategy is the only correct one is where you want to dehumidify (dry up) the air in order to defog/demist windows or prevent fog from forming on the windows under humid conditions. This function has a high safety aspect under the relevant conditions. In all other cases where fog up/defogging is not an issue, a variable setpoint is a feature that can give substantial energy savings. Variable setpoint means that the air is only cooled down to the level that is necessary to accomplish the desired comfort and no additional heating of the air is necessary. Fixed setpoints are typically in the range 2-5 º C where variable setpoints can get up to some 12-15 º C.

In order to have more energy efficient systems, different possibilities have been developed to control the supply of cold air according to the demand of the user.
The most common today is that a *variable displacement* compressor replaces the *fixed displacement* compressor. The variable displacement compressor can either be of the type *internally controlled* or of the type *externally controlled.* For a system with a variable displacement compressor, capacity control/freeze protection is carried out not by turning the compressor on and off but instead by adjusting the pumping capacity in relation to the actual demand by varying the displacement.

Another way to further reduce the heat load on the evaporator, and thereby the energy consumption, is to utilise the feature of recirculating some of the passenger compartment air. What determines the amount (i.e. the percentage) of air that can be recirculated, is the resulting air quality inside the vehicle. Recirculating air is also influencing the fogging up/defogging of windows and must therefore be used with great care.

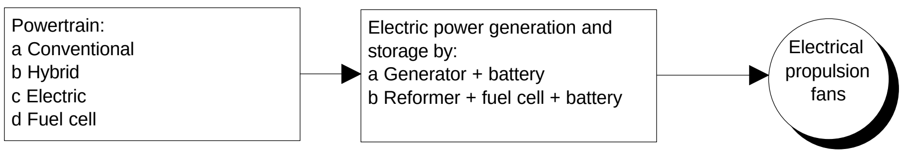
Fixed displacement compressors are always equipped with an electromagnetically controlled mechanical clutch that can turn the compressor on and off. Variable displacement compressors can either be equipped with the same type of clutch or can be clutchless. Specifically for externally controlled compressors, clutchless variants have become more common during the last few years. In almost all cases of a clutchless design, the belt pulley has an integrated "brake away" function that allows the pulley to turn freely should the compressor for some reason fail (seize). Clutchless designs offer some weight savings but on the other hand it prevents the compressor from being turned off during the cold (non A/C) season. Under these circumstances modern, variable displacement compressors can reduce the pumping capacity to almost zero or some 1-3 % of maximum capacity, but there will always be some additional friction losses associated with a clutchless design.

Except for still a very low number of electric vehicles with electrically driven compressors, all cars and trucks in production today have the belt drive from the engine crankshaft described above. This means that pumping capacity of the compressor increases with increasing engine speed. Together with the actual heat load on the evaporator (airflow, air temperature and humidity, and setpoint) and the actual cooling of the condenser (air temperature, vehicle speed/ cooling fan speed = condenser airflow) this determines the cycle rate (= time on/ time off) for a fixed displacement compressor and in the case of variable displacement compressor, the percentage of displacement utilised.

Electric fans

Additionally to the compressor drive an air conditioning system uses a forced airflow, achieved by a pair of electrically propelled fans, for the transport of air past the evaporator and condenser. The additional operation of these fans, specifically working for the air conditioning system, contributes to the overall load of the vehicle’s electrical system. This load also affects fuel consumption and thus also the emission of CO_2.

Figure 13: System configurations for the electrical propulsion of the fans.



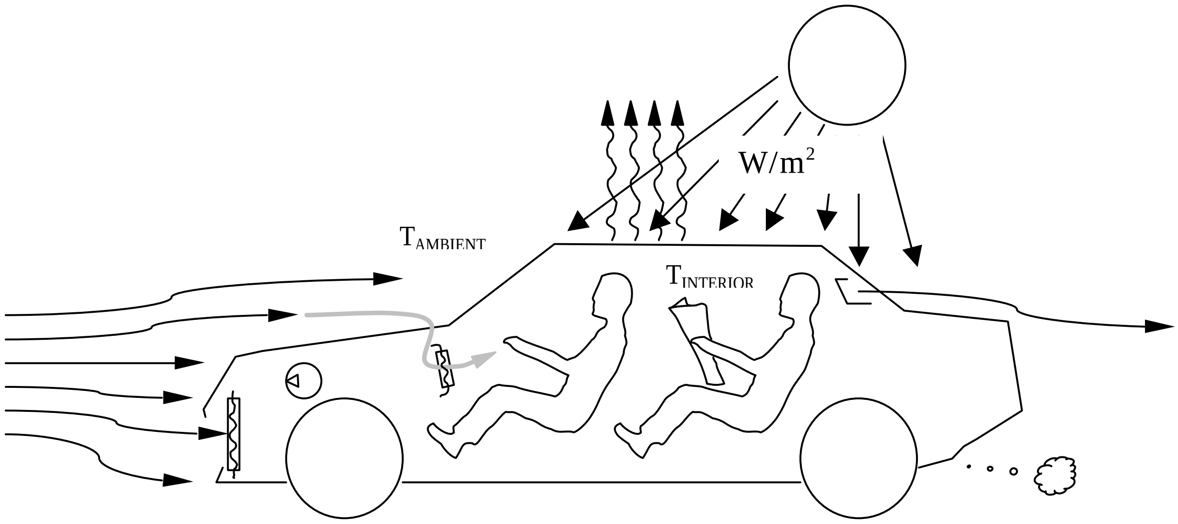
Demisting

For the purpose of clearing misted up windows an air conditioning system exploits its capability to dehumidify the moist air that enters the ventilation system, as indicated above. When moist air passes the evaporator the air can be cooled to below the dew point. The water (in vapour phase) condenses at the relatively cold evaporator. The water that is now in the fluid phase can run off the evaporator and leave the system (vehicle). This functionality requires that the air is cooled to below the dew point. Consequently the temperature of the forced airflow is often too low for blowing it directly in the passenger compartment, and has to be reheated to a level that meets the actual temperature demand.

4.1.3 Vehicle aspects

The required power that is needed to drive an air conditioning system depends amongst others on the demand for cold air. This demand is not only dependent on ambient conditions like temperature, humidity and solar load but also on some vehicle aspects. The vehicle aspects that are relevant for the amount of required power of the air conditioning system will be discussed briefly in this chapter.

Figure 14: A vehicle equipped with an air conditioner.



First of all the thermal insulation of the vehicle affects the amount of cold air that has to be supplied to the cabin. A well-insulated roof for example is not very efficient for loosing heat from the cabin by convection. Wind does stimulate the convective heat transfer from the cabin, but a well-insulated roof will diminish this effect.
On the other hand cool air (and hence 'cold') does get lost from the interior through ventilation. The ventilation system transports the cold fresh air from the air conditioning system through the vehicle and eventually to outside the vehicle in order to have a constant fresh air supply. Transporting cold air to outside the vehicle means that additional 'cold' has to be generated for maintaining the desired temperature. The volume of the interior is the main parameter here, and the possible use of air recirculation plays a secondary role.
Another form of thermal insulation is the insulation for solar radiation. A surface of glass allows solar radiation to enter the cabin of the vehicle, and thus directly heats up the cabin. The amount of glass, the insulation for solar radiation of the glass itself and the angle to which the windows are placed affect the amount of cold that has to be

supplied to the cabin in order to maintain the desired temperature. The type of vehicle (sedan, station wagon, hatch back) and the colour of the body play a role here.

During start-up the vehicle may have to be cooled down from a high (ambient) temperature to a low operating temperature. The energy required for this phase is dependent on the temperature difference and the heat capacity of the interior.

4.2 Auxiliary heaters

An in-vehicle air conditioning system is often a sales option on the basic version of a certain type of car. An auxiliary heating system, on the other hand, in some countries became a standard feature on passenger cars. For interior heating the usual system is one where the required heat is drawn from the engine’s coolant. But the trend on the engine’s increasing energy efficiency enforces other systems to be applied. With the increasing efficiency of the engine, too little waste heat from the engine’s coolant is available for usage in the heating system, especially in the warm-up phase. Nowadays some variations on the conventional heating system are known. Some of them work electrically and draw their energy for operation from the low voltage battery and the generator and thus indirectly from the engine. Others use fuel stored in the vehicle’s tank for a fuel fired heater. It is clear that these systems influence both the fuel consumption and the emissions. For this reason these systems will be discussed briefly in this chapter.

A fuel-fired heater operates stand-alone because this system only relies on the supply of fuel stored in the tank of the vehicle. The operation of this system is rather simple: inside a burner housing fuel is injected and mixed with air. A piëzo-electric ignition or a glow plug fires the mixture at start-up of the system. A fan forces the hot gases to blow along a gas to liquid or gas to gas heat exchanger. In this way it is possible to respectively heat-up the engine’s coolant or the air supplied to the vehicle’s interior. The exhaust gases leave the heater system. This type of heater allows a cabin heat-up and even an engine heat-up when the engine is not running and is therefore an interesting system for countries with very low ambient temperatures.

Electric heaters do not operate stand-alone, but fully rely on the electric power supplied by the vehicle’s low voltage battery and generator (as applied in a conventional powertrain). An electric heater system is very simple of construction. A PTC (Positive Temperature Coefficient) thermistor directly supplies the required heat to the engine’s coolant or to the air that is blown past the PTC element to the cabin. A PTC is a thermally sensitive semiconductor resistor. Its resistance sharply rises with the increase of the temperature. The opposite effect is used for heating: supplying electrical power to the PTC causes it to become highly resistive. The high resistance reduces the absorbed power. A state of equilibrium is then set up in which the electrically absorbed power equals the thermally dissipated power. The thermally dissipated power is used for heating a forced airflow directed to the cabin or for heating the coolant of the engine.

Next to the fuel fired heater and the electrical heater the visco-heater is a system that uses additional energy for operating. The principle of this heater is that the friction of oil between rotating plates causes the oil to heat up. The heat of the oil is transferred to the engine’s coolant by the use of a liquid to liquid heat exchanger. The additional energy for operation is drawn directly from the vehicle’s engine by mechanical propulsion of the friction plates. Another possibility is that electrical power is supplied by the vehicle's generator and low voltage battery for the electrical propulsion of the friction plates.

In countries with very cold climates externally powered electric heaters have been used for years. They are used to aid starting from cold. Since the engine then starts with a pre-warmed engine, their use results in a significant reduction in cold start exhaust emissions, and may be assumed to result in some reduction in cold start fuel consumption too. The balance between the additional CO_2-emission resulting from the use of the external power source and the possible gain in CO_2 from the fact that the start is made with a pre-warmed engine is very difficult to determine and would need a thorough investigation into the average length of time the external power is used and the exact reduction in consumption following the start.

4.3 Developments

During a workshop with the relevant industry it became clear that the conventional air conditioning systems that were discussed in the paragraph above have a long history of development on making the system more efficient on energy consumption and more accurate on temperature control. Additional to the developments on these conventional systems other systems for interior climate control have been developed, some also fitted with a better functionality for safety and convenience. Such developments, both on the conventional systems and on completely new systems, will be discussed in the next paragraphs.

Electrically driven compressor
A development already beginning to appear on the market is that of the electrically driven compressor. The main characteristic of such an approach is that it allows the use of speed control, since the speed of the compressor has then become independent from that of the engine. This can lead to significant power savings. On the reverse side stands the fact that the conversion of engine produced mechanical power into electrical power introduces additional conversion losses. The expectation is that such developments will really take off when special 42 V electrical board systems are introduced, possibly with their own fuel cell driven electricity generation (which would avoid the conversion step mentioned).

Refrigerant
Current in-vehicle air conditioning systems often use R134a (HFC-134a) as a refrigerant. This refrigerant has a Global Warming Potential (GWP) of 1300 [Sumantran]. An increasing concern over the high GWP of R134a has led the international heating, ventilation and A/C industries to look at other options. Various alternative refrigerants have been assessed for their potential to replace R134a in conventional air conditioning systems. But the need to replace R134a also led to the development of new systems that are able to use refrigerants that are less severe with respect to their GWP. The alternative refrigerants may have consequences for the set-up of the conventional air conditioning system. For example some refrigerants are flammable and therefore require a secondary loop in the air conditioning system. This type of system would prevent leaking refrigerant from entering the passenger compartment. Another example is the use of CO_2 (R744) in a heat pump system. Both of these systems will be discussed in this paragraph.

Air conditioning system with a Suction Line Heat eXchanger (SLHX)
This system is more or less a conventional air conditioning system [Pressner 2001]. An extra heat exchanger is added, however, to transfer heat from the condenser outlet flow to the compressor inlet flow (‘suction line’). The system can adjust the temperature more accurately. Therefore this system can improve the efficiency of the conventional R134a cycle.

Heat pump (with CO_2 as a working fluid)
A heat pump is a device that accepts heat at one or more temperatures and rejects heat at a higher temperature. The heat pump comes with the advantage that it can act as a refrigerator or as a heater. A recently developed system uses CO_2 as a working fluid, which has the advantage of a low GWP, compared to most other working fluids/refrigerants. Furthermore, this system may have a high potential to be efficient. The system is reported as having sufficient performance to be used as a heater even in a vehicle operating under low ambient temperatures.

Absorption
An absorption system works in the same manner as the conventional vapour compression system with exception that the compressor is replaced with a circuit that absorbs vapour at a low pressure and desorbs it at a higher pressure. For this circuit a solid as well as a fluid absorption material can be used. This system also comes with the advantage that it can act as a refrigerator or as a heater.

CO_2 / co-fluid system
In this system the conventional vapour compression principle and the absorption principle are combined [Spauschus 1999, Seeton 2000]. This combination of principles is chosen because a conventional cooling system with CO_2 requires a high operating pressure and hence special attention regarding strength and durability. The co-fluid system allows a lower operating pressure to be used. The system uses a mixture of CO_2 and a fluid (the co-fluid) in which CO_2 is highly soluble.

Secondary loop A/C
A secondary loop system is build up of two separate circuits. [Ghodbane 2000] The reason for separating the system into two is in fact the wish to use alternatives to the high GWP HFC-134a as refrigerants. Some interesting alternative refrigerants (hydrocarbon, R152a, ammonia) are hazardous to health, however, and therefore require a secondary circuit to isolate the refrigerants from the passenger compartment.
A variation on this system was found in the literature [Schmid 2000, Kampf 2001]. In this system a ‘cooling battery’ is integrated in the secondary loop. This principle of thermal storage of cold has the advantage that during parking the cabin can be maintained at a comfortable temperature for a certain length of time.

Weight
Along with the developments on the system configurations that focus on the optimisation of efficiency, comfort and safety, developments are made on weight reduction of the individual components of the systems. For conventional systems this probably leads to an overall weight reduction. This might be slightly offset by the growing complexity of conventional systems, because more components are used. For the use of alternative systems it is not known what the consequences are for the total system weight.

5 Test methods for air conditioners

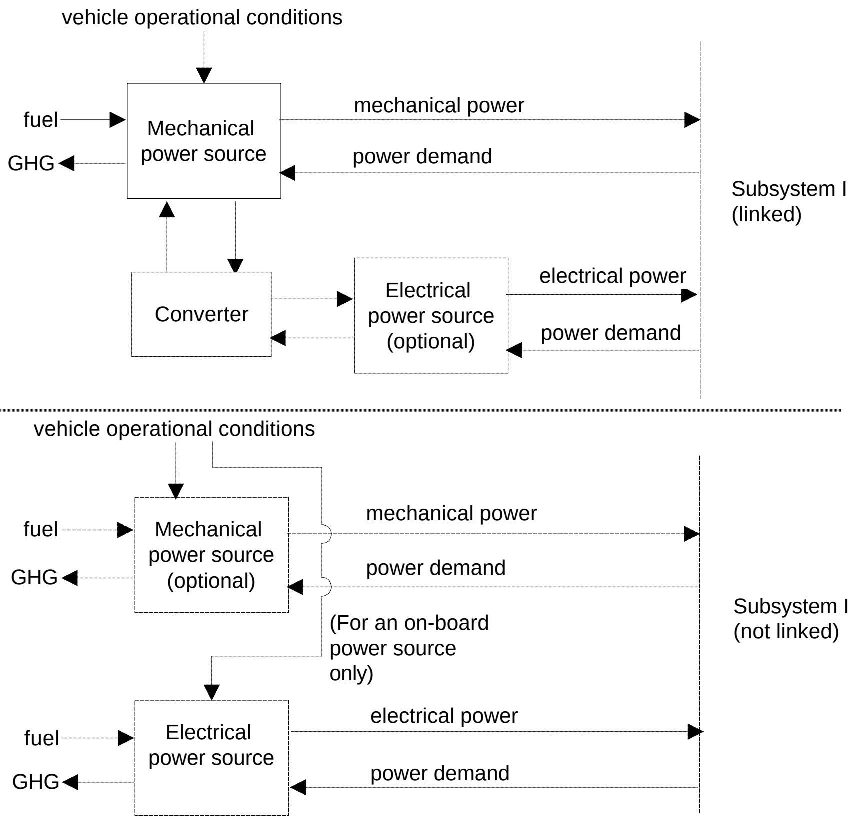
5.1 General considerations

The aspects to be taken into account for the purpose of testing air conditioners were discussed in Chapter 2. They stem from the wide variety of possible systems, as outlined in Chapter 4, and their different characteristics. Any procedure proposed has to be applicable to all configurations currently on the market or expected in the near (or even further) future. It is obvious that the simplest approach to establish the environmental performance of any auxiliary system would be to perform a relevant test twice: the first time with the auxiliary system switched off and the second time with the auxiliary system switched on. The subtraction of the results of the second and the first test gives the effect of the auxiliary system. This set-up in itself is rather straightforward to perform, but would lead to at least doubling the amount of test to type approve a vehicle. The financial and timing implications of such a procedure however would be severe for the automotive industry.
Taking this implications into consideration, the contractor looked for intelligent options in order to decrease the amount of actual test work, without compromising the basic requires of the procedure. This lead to a set-up in which car types on the market are grouped into certain families enabling one test set-up per family (instead of one test per type). The basis for this family building process has been similarities between vehicle types. These similarities on vehicle construction level have been split up in 3 groups (subsystems):

- Subsystem I: the power generation
- Subsystem II: the air conditioner system
- Subsystem III: the vehicle environment

These systems can be considered on two levels: the physical level and the system level. The physical level will be dealt with first. In the schemes it is represented by the solid horizontal lines, with arrows moving to the right. For this reason the findings of the previous chapters are represented in a simplified scheme in Figures 15-17. In these figures “airconditioners” have been used as an example for an auxiliary equipment.

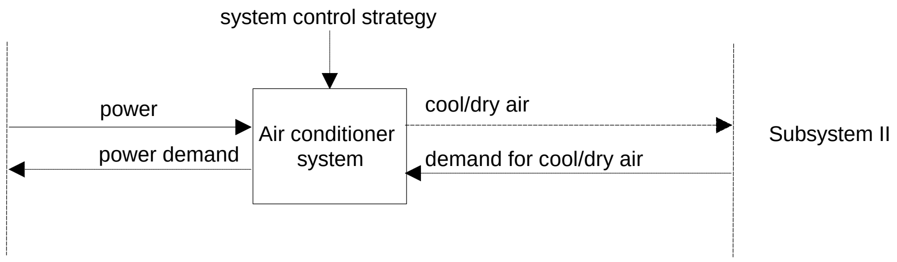
Figure 15: Subsystem I, two variants: linked and not linked.



<u>Subsystem I</u> can either generate mechanical power, or electrical power, or a combination. When it generates mechanical power, in practice it will consist of the vehicle's propulsion engine. In that case the greenhouse effect will consist of additional emission of GHGs through the engine exhaust. This additional emission is dependent on the vehicle operating conditions as the main variable, and can only be determined in any exact way by comparing situations with and without this extra mechanical load for those operating conditions, in whatever way.

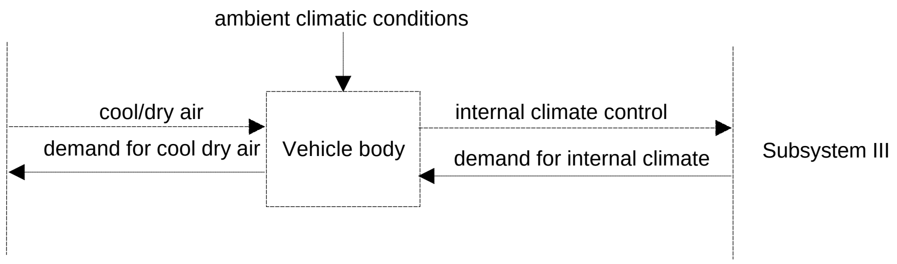
In the case of electrical power there are three further possibilities. In the first place the electrical power may in the end also be generated by the engine (Fig. 15, upper part: linked). The 'source' of the electrical power then simply consists of an energy converter with an input of mechanical power also generated by the engine and an output of electrical power, and the end effect is also measurable in the engine exhaust. In the second place the source of electrical power may be a self-contained generation system, such as a fuel cell (see Fig. 15, lower part: not linked). The greenhouse effect then consists of the share of the total GH-effect of that system that is attributable to the air conditioner system. In the third place the source of electrical power may be an off-board system, such as a power station; this possibility is also covered by Fig. 15, lower part, with the exception that the GHG consequences of the power demand will not be dependent on the vehicle operational conditions. In that case the GH-effect is that of the external source for the total electrical power derived from that external source that is attributable to the air conditioner system.

Figure 16: Subsystem II.



<u>Subsystem II</u> on the physical level converts power into cool and/or dry air. The relation between these in- and outputs is system dependent, with the system control strategy as the main variable. The relation should be relatively easy to determine.

Figure 17: Subsystem III.



<u>Subsystem III</u> on the physical level produces an internal climate on the basis of the cool/dry air provided, in interaction with the vehicle's characteristics, and with the ambient climatic conditions as the main variable. Because of this interaction with the characteristics of the vehicle body, the relationship is vehicle dependent.

On the *system level* the relations work in the opposite direction: There is a demand for a controlled inner climate, which in the end causes some greenhouse effect. These relations are indicated by the dotted horizontal lines and arrows pointing to the left. The relation starts then with subsystem III, which has a demand for an inner climate as an input and a demand for cool/dry air as an output. Subsystem II has this same demand for cool/dry air as input and a power demand as an output. Subsystem I finally has this power demand as an input and the GH-effect as an output.

On further consideration it can be concluded that the input/output relation of subsystem III is fully dependent on the vehicle (in fact the characteristics of the vehicle body). The main variable (ambient climatic conditions) can be standardised, if needs be with regional differentiation. The input/output relation of subsystem II is fully dependent on the air conditioner system, including the main variable (system control strategy). The input/output relation of subsystem I is an interaction between the vehicle characteristics (in this case the power generation part) and the air conditioner system. It is the vehicle power generation system that controls the efficiency of the power generation and hence the relation between power demand and greenhouse effect (for a given set of vehicle operational conditions), but this relation will be different for mechanical power and electrical power, and it is the air conditioner system that determines the kind of power needed. The main variable (vehicle operational conditions) may again be standardised.

5.2 Overview of existing test protocols

Of all the auxiliary systems for comfort and safety in passenger cars, the air conditioning system uses relatively much energy. Most of the current air conditioning systems draw this energy directly from the vehicle's engine and thus indirectly from the fuel stored in the fuel tank as was shown in Chapter 4. Because the air conditioning system does not operate stand-alone but in most cases depends on the power supply from an engine, its required operating power directly affects the fuel consumption (FC), the CO_2-emission and also the other regulated emissions (HC, NO_X, CO and PM). It is clear that the amount of extra fuel consumed by the use of an air conditioning system is dependent on many factors. Apart from the quality and set-up of the air conditioning system itself, the vehicle's engine, body and interior have a clear influence on the additional amount of fuel consumed by the use of an air conditioning system.

When the air conditioning is tested in the vehicle, that is with the vehicle driving a given driving cycle and with the air conditioning operating under predefined ambient conditions, the quality of the total air conditioning system effect with respect to FC is tested. This method takes into account the influence on engine load and the other vehicle dependent aspects already mentioned, such as thermal insulation, air-recirculation etc. Current test procedures globally use this strategy for their testing method.

The best known test procedure for testing an air conditioning system with respect to its influence on Fuel Consumption and emissions is the legislated SFTP (Supplemental Federal Test Procedure; 40 CFR 86.132-00, 86.160-00 and 86.161-00 are the additional prescriptions for testing vehicles with air conditioners) used in the United States. This SFTP is the already existing FTP procedure for type-approval testing, augmented with an extra driving cycle (SC03) especially for A/C testing, and a driving cycle for high speed driving (US 06). The SFTP has been implemented in the U.S. in the standard test procedure for emissions in the year 2001, starting with 25% of the model year 2001vehicles being subject to the SFTP going to 100% for the model year 2004 vehicles.

For the SC03 part special conditions are required. Before the actual test the vehicle is driving a prescribed driving cycle on a chassis dynamometer with the air conditioner switched on. Manual controlled systems have to be set to full cool, maximum fan speed, A/C mode switched to maximum and the airflow set to recirculate. Automatically controlled systems are set to 72°F (~22°C) instead of "full cool". Then the vehicle has to be thermally soaked for 10 minutes (engine and air conditioner switched off). After this soak period the SC03 driving cycle is carried out on a chassis dynamometer in a climatic chamber at 35 °C, 40% relative humidity, and a solar load of 850 W/m^2, with the same system settings as in the preconditioning test. The results from all the cycle parts are weighted (FTP, SC03 and US06) according to the following distribution: 33%, 39% and 28% respectively.

Apart from the SFTP SC 03 test, other test methods have been developed on an ad hoc basis for testing the use of an air conditioning system on fuel consumption and emissions. From the table it becomes clear that the three procedures all use a fixed temperature and humidity during a test. Two procedures did take solar radiation into account. One by applying a real solar load, and one by increasing the ambient temperature as a correction for solar radiation. In the table below examples of the existing procedures used for testing air conditioning systems are given.

Table 5: Overview of test procedures.

Source	**Temp [°C]**	**RH [%]**	**Solar Radiation**	**Test cycle**	**Addition of results?**
SFTP SC 03	35	40	850 W/m2	SC 03	Results are weighted according to a given distribution over 3 driving cycle parts.
ADEME/UTAC	30, 40	50	+5^{O}C	NEDC	No, the results are used as separate factors.
TNO	28	60	No	TNO real world	No, the results are used as separate factors.

The procedures by ADEME/UTAC and SFTP seem to specify lower humidities, but the absolute humidities are 14.3 (SFTP), 13.3 (ADEME/UTAC at 30°C) and 14.2 (TNO) g/kg of dry air.

5.3 Standardisation of the test conditions

For the test and the representation of the test results, whether according to option 1 or option 2 (see paragraph 6.3), the following items need to be standardised:

- The ambient temperature
- The required inner temperature
- The ambient relative humidity
- The ambient radiation intensity
- The driving cycle

For inventories the year-round frequency of use is also required.
Obviously some of these items vary in the field with the regional climatic zone.
Not all of these items do play a role in the actual testing as outlined in the proposal as outlined later. But they would do so in the investigation that would determine the average air change rate needed to maintain the required inner climate under the standardised conditions.

The ambient conditions
Obviously the ambient temperature and humidity, as well as radiation intensity, will vary with the time of the year and with the regional climatic zone in Europe. On the other hand the ambient conditions during actual use of the air conditioner may be more or less similar, while it is mainly the frequency of such conditions that varies. The most practical approach therefore seems to be to standardise one set of ambient conditions and only to vary the frequency of use per climatic zone.

There are several options for the determination of such conditions. One may go for the mean conditions during the actual use of such equipment, or for the worst case situation, or (so as to avoid extremes) for the 90% worst case. This last approach (90% worst case) was chosen for the European fuel evaporation test. The temperatures and temperature profile of that discussion might be used for the air conditioner test. The maximum temperature for the evaporation test is 35 °C; the average temperature for the period 8.00 to 20.00 hours is 30 °C (for the period 8.00 to 18.00 hours it would be 31 °C). Such a value would be best for emission factor use. On the other hand the real difference between air conditioning systems come to light especially under part load conditions. This would point to the necessity to select a temperature in the range 25-30 °C for labelling use. As a tentative value 28 °C is proposed. This temperature falls within the temperature range acceptable for the standard type test.

Solar radiation

The vehicle's body and glazing absorb heat from solar radiation, the body and glazing reflect a certain amount of heat from solar radiation and only the glazing transmits a certain amount of heat from solar radiation, whereas the vehicles interior (e.g. dashboard) absorbs and reflects a certain amount of heat from solar radiation transmitted through the glazing.

To what extend solar radiation contributes to the total amount of heat transfer is not very well known. In the past different models were developed for heat transfer, taking solar radiation into account, in order to give insight into the level of comfort for the driver and passengers. The models were able to calculate the effect of e.g. solar reflective glazing on the level of comfort. Nowadays the effect of solar radiation is important for the matter of energy needed from the air conditioner to cool down the interior. It can be derived from the complexity of the processes going on that the contribution of solar radiation is dependent on many variables and that the contribution of solar radiation cannot be calculated easily. From the literature some indications can be found, however, that the contribution of heat transfer to a vehicle's cabin through solar radiation is significant regarding the amount of energy that is additionally required indirectly from the fuel in order to drive the air conditioner system:

NREL did investigate the effect of solar reflective glazing on a Plymouth Breeze, equipped with a climate control system, on fuel economy. The solar gain decrease amounted to 27%, whereas Fuel Consumption can decrease 2 to 3,5% depending on the driving situation when the compressor is proportionally downsized.

Barbusse reported 45% for the contribution of solar radiation to the total heat transfer, but did not specify how this figure was obtained.

UTAC did add 5K to the representative ambient temperature in order to compensate for solar radiation during chassis dynamometer tests in a climatic chamber.

Notwithstanding the complexity of a fully developed calculation, a simple calculation shows that a car with 1,5 to 2 m^2 of glazing, facing in the direction of the sun, at a sun load of 1kW per square meter and no solar reflective effect of the glazing, will have a heat transfer to the cabin, caused by solar radiation through the glazing only, that lies in the order of 1,5 to 2 kW. This and the figures reported by others indicate that solar radiation contributes significantly to the heat transfer to the vehicles cabin and thus to the amount of cold air that has to be supplied to the vehicles cabin. This strongly points to the necessity of incorporating simulated solar radiation into the test, even although this does mean a significant complication of the test method!

The actual degree of solar radiation that has to be used for the tests should still be determined from European weather data, but harmonisation with currently used methods (US) should be considered in order to reduce test facility costs.

The required inner climate
Although different people may (and do) prefer different inner climatic conditions, and whereas such preferences may (and do) even show a systematic variation with countries or regions of the world, the most practical approach seems to be to standardise one set of required inner climatic conditions.

The year round frequency of use
The year round frequency of use may vary with the climatic zone within Europe, i.e. on the frequency with which high temperatures occur, although the trend seems to be to switch on the air conditioner at all times and to let the system control determine the extent of the operation, depending on the outside/inside temperature difference.

The driving cycle
The most logical choice for the driving cycle would be the standardised European emission test cycle. This cycle is also used for the current fuel consumption test. Use of this cycle for the air conditioner test would have the pragmatically and indeed desired result that the figures for the basic vehicle and the vehicle with air conditioner (or, alternatively, for the air conditioner itself) are directly comparable.

In itself the driving cycle currently in use can be significantly criticised for a lack of representativity for modern driving, and urgently needs revision for a variety of reasons and purposes. Especially when accurate emission factors of air conditioner-equipped cars are required, the use of ‘real-world’ driving cycles is unavoidable. But this is a different issue that cannot be dealt with in this context. If the purpose of the exercise is defined as ‘labelling’ the real question is whether the existing driving cycle would or would not give a more or less representative picture of the *additional* GHG emissions as a result of the use of an air conditioner, rather than whether the combined overall figure is representative for real-life circumstances. In the absence of any real data it is felt that the determination of the *additional* effects may be less dependent on the representativity of the cycle than the determination of the figure for the basic vehicle, or consequently the combined overall figure. But any hard conclusions would of necessity need such real data. If the purpose of the exercise is defined as ‘emission factors’ the use of a ‘real-world’ driving cycle becomes an unavoidable issue.

Climatic zones
One may either label the systems per distance of driving cycle with switched on air conditioner and some kind of average ambient conditions, or for the likely year-round additional effect on the basis of an assumed average annual mileage. In the latter case the effect of an air conditioner system on the emission of GHGs is directly proportional to the frequency of use. This frequency is dependent on the climatic zone. It is here proposed to differentiate into no more than three climatic zones: i.e. the Nordic countries, the central EU and what could be roughly termed the Mediterranean area. On the basis of annual temperature profiles it is more specifically proposed that zone 1 consists of the countries mainly or completely north of 55° NL (northern latitude), but excluding Denmark. In the current composition of the EU these are the countries north of the Baltic. Zone 2 would consist of the countries mainly or completely between 45° NL and 55° NL (but including Denmark). Zone 3 would then consist of the countries

mainly or completely south of 45° NL. The only present EU Member State that according to this definition would fall into two climatic zones is France, although this would have more area in zone 2 than in zone 3. An alternative proposal would be that countries could determine for themselves for which climatic zone they want to label their vehicles. The characteristic frequencies of use will have to be determined. When emission factors need to be determined, much more needs to be known about local climatic data and about the exact patterns of use by the customers. Table 6 shows the preliminary proposed conditions for a labelling test.

Table 6: The proposed standard test conditions for cooling.

Condition	Unit	Value	Comments
Ambient temperature	°C	26	This value should be adjusted to the temperature that is best represented in the annual (daytime) temperature distribution.
Required inner temperature	°C	21	Standardised location
Ambient humidity	%	60	at 26°C (ca.13 g/kg dry air)
Ambient radiation intensity set point	W/m^2	850	To be reviewed from the climate data
Vehicle driving cycle	--	Current emission test	To be reviewed in general context
Frequency of use:			
Zone 1	%	6	Northern EU
Zone 2	%	11	Central EU
Zone 3	%	33	Southern EU

5.4 Conformity of the test conditions

A range of conformity of the test conditions has to be defined for every parameter or instrument that is relevant for the final outcome of the tests, here mainly considering the functionality, workability and costs. In the United States the SFTP has been set up for measuring the effect on fuel consumption of the use of an air conditioner system in a passenger car. In the test procedure of this SFTP the requirements for the tests are described. Because the SFTP is designed to measure the effect of the air conditioner under an ambient condition that is almost similar to the one proposed in this report it is worth the effort to look at the test requirements of the SFTP. Besides it can be assumed that the requirements are introduced keeping in mind that the procedure needs to be workable and costs effective.
Below a summary is given of the aspects that can be pointed out as matters that need a certain prescribed level of conformity/accuracy (40CFR – Chapter I – Part 86 paragraph 86.161-00). The list is meant as a guide for further research that should assess the requirements for the procedure in detail when the procedure is in it's final stage of development.

Ambient temperature
The ambient temperature under which the vehicle is operated is an important parameter considering its influence on the additional fuel consumption caused by the air conditioner. For this reason a range of conformity has to be defined. The SFTP values

are: a conformity range of ±2 ^{O}F on average over the complete test and ±5 ^{O}F instantaneous, in degrees Kelvin this is 1K and 3K respectively.

Ambient humidity
For the ambient humidity no range of conformity is prescribed in the SFTP. A range should be defined, however, taking into account the capability of the test cell equipment. In the EU regulations for type approval on exhaust gas emissions the range of humidity is very wide (5,5 – 12,2 g/kg dry air). For the type approval on evaporative emissions no range is prescribed. For the testing of air conditioners a more narrow range should be defined because the humidity is an important parameter considering it's influence on the load of the air conditioner. The next range is proposed: a minimum of 11,5 g/kg and a maximum of 13,5 g/kg being approximately 55 and 64 % relative humidity at 26 ^{O}C.

Required inner temperature and A/C-mode
In the SFTP a temperature set point of 22^{O}C is prescribed for automatic air conditioner systems. For manual systems the 'full cool' mode is prescribed for the complete test. In the proposal of Chapter 6 a maximum temperature [21^{O}C] that has to be reached within a given time [8 minutes] represents a very close to a realistic situation which makes the comparative assessment of different systems on fuel consumption more reliable. So for the manual controlled systems this leaves the option to (manually) stabilise the temperature at or below 21^{O}C. In the case of adjusting an electrical heating device the additional electrical energy should be measured also. In the SFTP regulations no range of conformation is described. For this procedure it is proposed to use an accuracy range for the inner temperature measurement of ±0,5^{O}C.

Solar load
In the USFTP procedure special requirements are described for the solar load. The following matters have been taken into account:
- Type of radiant energy emitters
- Placement of the vehicle
- Radiant energy intensity set point accuracy
- Spectral distribution
- Bandwidth [nm]
- The angle of incidence
- Radiant energy uniformity tolerance
- Radiant energy uniformity measurement time interval
- Radiant energy intensity location of measurement
- Radiant energy intensity instrument specification

It is proposed to review these requirements in detail when the design of the procedure is in its final stage.

Vehicle frontal air flow
In the current EU test procedure for the measurement of the fuel consumption, requirements are made for the vehicles frontal airflow that are not very extensive. Because the functionality of the air conditioner system depends on the exchange of heat at the evaporator, for a large part provided by driving wind, it can be stated that the current requirements do not suffice with respect to a realistic simulation of the conditions.

In the USFTP the Administrator approves a frontal air flow based on “blower in box” technology as an acceptable simulation of ambient air flow cooling for the air conditioning compressor and engine, provided that the following requirements are fulfilled (40CFR – Chapter I – Part 86 paragraph 86.161-00):

- The minimum airflow nozzle discharge area must be equal or exceed the vehicle frontal inlet area. Optimum discharge area is 18 square feet (4.25 x 4.25), however, other sizes can be used.
- Airflow volumes must be proportional to vehicle speed. With the above optimum discharge size, the fan volume would vary from 0 cubic feet/minute (cfm) at 0 mph to approximately 95.000 cfm at 60 mph. If this fan is the only source of cell air circulation or if the fan operational mechanics make the 0 mph air flow requirement impractical, air flow of 2 mph or less will be allowed at 0 mph vehicle speed.
- The fan air flow velocity vector perpendicular to the axial flow velocity vector shall be less than 10 percent of the mean velocity measured at fan speeds corresponding vehicle speeds of 20 and 40 mph.
- The fan discharge nozzle must be located 2 to 3 feet from the vehicle and 0 to 6 inches above the test cell floor during air conditioning testing. This applies to non-wind tunnel environmental test cells only.

These are the main requirements that describe the set-up of the system for the vehicle frontal airflow. Next to these requirements there are some additional requirements on how to check the conformity of the airflow.

6 Tentative proposal of a method

6.1 General conditions

In the introduction (Chapter 1, the bullets of the second paragraph) it was argued that the set-up of a test method is, inter alia, dependent on the purpose of the exercise. The relevant catchwords were identified as 'emission factor' and 'labelling'. Labelling was defined as the key issue. This points at the need for a procedure that:

- is able to produce relevant customer information
- therefore does not have to be ultimately accurate, but
- results in a defined FC based ranking of systems used

Based on these conditions a tentative proposal for a method was made.
From discussions with the industry it follows that there is a great variety of vehicle air conditioner system combinations possible. On the one hand any given basic car model is usually offered in a rather large number of varieties, such as body variants, colours and engines. On the other hand air conditioner systems do come in a large number of variants too. Not only do car manufacturers, as a rule, obtain their systems from a number of suppliers, but they do not get them delivered as full systems, but rather as individual components (compressors, evaporators, condensers). A particular manufacturer gave, by way of example, the information that a certain popular model was delivered with 20 different system variants and 10 different engines, not counting body styles, let alone body colours. This strongly points to the necessity of a 'family system' in combination with a 'worst case' approach. Such an approach would be perfectly feasible in a labelling exercise, but much less so in an emission factor determination. For this reason it will be assumed hereafter that 'labelling' is the purpose of the test. Labelling would serve both the purpose of consumer information and the need for an incentive for the industry to develop and install energy efficient systems (so as to reduce the impact of air conditioners on the environment). Emission factors could only serve for establishing such impact, but not for reducing it. Our suggestion is that the society as a whole would be much better off to go for:

1. A simplified labelling procedure (and not to spend the extra money needed for an exact determination of the exact CO_2-effects of *all* vehicle/system combinations), and
2. To spend only a fraction of that money instead on a dedicated programme specially set up to determine these emission factors. Such a programme could involve on the one hand a much more limited but still characteristic number of vehicles, but on the other hand measure them in a much more involved and accurate way.

In the following paragraphs, therefore, a possible approach for a test procedure fit for labelling will be elaborated which is a 'modal' method because the procedure is split up into sub-systems. This set up of the procedure leaves the possibility to base parts of the procedure on modelling or to use default values for systems. **This proposal has been worked out in principle: it describes a methodology, although it does not yet contain a fully elaborated text.** It outlines the basic approach, of which certain concrete elements (especially numerical values) still have to be established in their final form.

6.2 Tentative proposal

General requirements

The following general requirements have been taken as the starting point of the approach:

- It should be possible to perform the test as much as possible in existing laboratories
- The test method should not require major modifications to the test vehicle
- The test method should be robust and reproducible
- The test result should be sufficiently meaningful for the consumer, but without the requirement of an absolute numerical accuracy (since the purpose is labelling)

Such an approach does require a fair degree of ‘standardisation’, which on the one hand inevitably produces somewhat schematic end results (but so does the standard fuel consumption test), yet on the other hand will allow a sufficient degree of ‘modelling’, which can simplify the determination of results in a significant way.

The ‘family approach’

From discussions with the industry it became clear that the number of permutations of system components that together form a complete vehicle/engine/air-conditioning system can be very large. It was therefore decided to adopt a ‘family approach’ so as to minimise the necessary amount of testing. This family approach does concern:

- A sufficient degree of variation in the basic vehicle, incorporating:
  - a certain range of variations within the body
  - the complete range of engines available within that body family
- The complete range of variations in air-conditioning systems available within this vehicle family.

This means that *on the ‘parent’ air-conditioning system, as installed in the ‘reference vehicle’ variant, a number of basic characteristics has to be measured, that subsequently can be used to skip a number of steps in the measuring of further family members*. The vehicle manufacturer will always have the option, however, to avoid these additional measurements and to measure any further family member in full.

The basic test approach

The basic approach of this proposal for a test methodology is to determine the necessary input energy needed to drive the compressor and the further auxiliaries (i.e. the fans) in the test cycle according to 80/1268/EEC under characteristic circumstances of use.
The basic approach focuses on three sub-systems separately, because these three systems all have their (different) impact on the final result. The three sub-systems are:

- the vehicle body
- the air conditioner
- the engine

The characteristic circumstances of use require the use of a climatic chamber. It is suggested that the use of a climatic test cell as used for the type VI test (the low temperature test) could be fitted out for such testing. The energy input determined in this way should then be the basis for the energy label. Since the energy ‘consumption’ of the compressor is primarily dependent on its speed, and secondarily on its control, the testing of subsequent family members can be performed as a bench test consisting of a compressor speed cycle with a check on the required system output (in terms of flow and outlet temperature).

The proposed approach is graphically outlined in the flowchart on page [53]. The procedure is divided over four columns. The first column represents the existing standard test, as performed under Directive 80/1268/EEC. The second column represents the testing in the climatic chamber. The third column represents the testing done on a separate test stand, outside the climatic chamber. And the last column represents calculation procedures that only are deskwork. The major aim has been to skip in the case of family members the work in column 2 (the climatic chamber), in order to limit costs, and to shift as much as possible to column 4 (calculating procedures). So as to enable this it turned out to be necessary

- to perform some additional measurements during the procedure with the parent in the climatic chamber that has to be performed anyway, and which then can be used to check the performance of family members outside the climatic chamber, and
- to perform one measurement per family member on a system test stand where no vehicle is needed).

All of this has led to a procedure that looks relatively complicated at first sight, but which asks for the minimum of actual testing, and is reasonably straightforward for the extension of an already granted certification to family members, both on the system side and on the vehicle side. In the final reckoning this will save unnecessary work and costs.

6.3 Description of the methodology

The family definition

The proposed methodology does start with subsystem III. This step needs to determine the specific need for cool air for the vehicle family. It is obvious that it would be far too detailed to determine the need for cool air for each individual body type, let alone body colour. So as to make the procedure workable at all, the determination has to be performed for a family of bodies. The main question here is how to define such a family. A too narrow definition would greatly increase the number of permutations and therefore tests. A too wide definition would make the final result insufficiently accurate. The industry would prefer to limit the possible variants to models, but just on the basis of a verbal term this might be too wide a definition. Our proposal would be to define a model on the basis of the following characteristics:

- Same basic vehicle model indication [1)]
- Same interior volume, with a margin of ± [10] % [2)]
- Same exterior surface, with a margin of ± [10] % [2)]
- Same total glass surface, with a margin of ± [10] %
- Same angle of the windscreen, measured over the centreline, with a margin of ± [10] degrees
- Same angle of the B-post, with a margin of ± [10] degrees
- Same angle of the rear window, measured over the centreline, with a margin of ± [20] degrees [2)]
- Same reflective coefficient of the glass (possibly limited to that of the windscreen), with a margin of ± [10]%

Notes:

[1)] It will be necessary to cater for the possibility that the same ‘model’ is also marketed under another brand name, and hence under another model name (e.g. VW Lupo/Seat Arosa; or Fiat Ulysse/Lancia Z/Peugeot 806/Citroen Evasion; etc.)

2) It could be further studied if it is possible to handle model variants, such as sedan, hatchback (and stationcar) through the use of calculation: i.e. correction factors for volume and surface.

Hereafter the proposed methodology based on family definitions will be described. This methodology is characterised by a number of options at various stages, in order to make the approach as workable as possible for the manufacturers, without losing accuracy to an unacceptable extent. So as to assist in understanding, the whole procedure is summarised the table below and in a flow chart at the end of this paragraph.

Table 7: The proposed test approach.

Step concerns	Type of action	Input	Output
STEP 1 Determination A/C performance needed	Measurement on parent Check on family members	Temperature profile	Required CFF [K*kg]
STEP 2 a) Determination of A/C drive energy b) Determination of compressor speeds	Measurement on 'worst case' system	CFF of parent Standard test cycle	Drive energy over cycle X [kWh] mech. Y [kWh] electr.
STEP 3 Determination of: a) additional FC and CO_2 b) engine efficiency factor of parent (for use with family members)	Measurement/ calculation	Output of STEP 2 of family member, or STEP 3b of parent	FC [litre/test] and CO_2 [g/test] Reference engine efficiency factor
PRESENTATION Effect on FC and CO_2 of air conditioner per test	Calculation	Output of STEP 3	LABEL FC [litre/100 km] CO_2 [kg/100 km]

Parent air conditioner system in reference vehicle: STEP 1

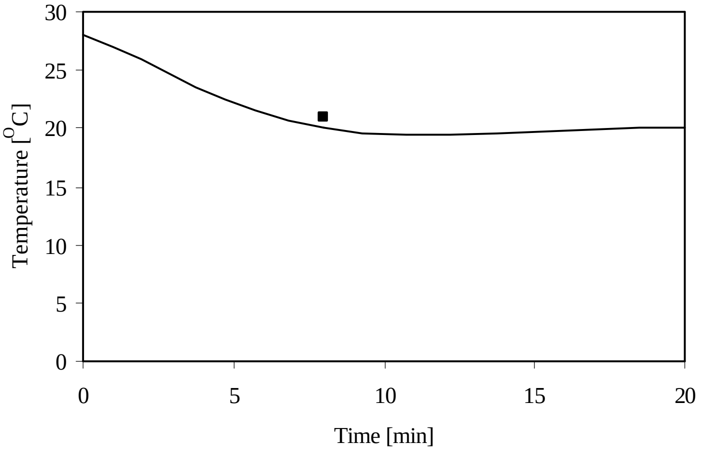
Determination of the necessary flow and outlet temperature of the air conditioner system.

For this determination a climatic chamber will be needed. The cooling performance of an air conditioner system is checked for two requirements:

1. Cooling down of the interior of the vehicle that has been subjected to a simulated parking, to a defined interior temperature within a given length of time. This temperature/time point may be regarded as a 'way point' (See Figure 18) that needs to be 'passed' by the temperature/time curve on the 'correct side', i.e. in an equal or shorter time and/or at an equal or lower temperature.
2. Maintaining that interior temperature, once it has been reached, for the remainder of the test cycle. For the purpose of the test 'maintaining' is taken to mean not exceeding the temperature of the 'way point' mentioned under '1'. If, on the other

hand, the interior temperature of the vehicle drops to a lower value this is regarded as acceptable for the test.

Figure 18: example of the course of the cabin temperature during a test passing the defined waypoint at the correct side.



It is proposed that the cooling down phase has to guarantee that a vehicle interior temperature of [21] °C has to be reached within [8] minutes from the start, and that the stabilisation phase has to guarantee that this temperature is not exceeded during the remainder of the test. The vehicle's interior temperature has to be measured at a standardised location. It is suggested that this is done at the level of the head of the driver. For the height and the position of the driver the standardised values for the 50-percentile dummy of the standardised crash test could be taken; these are very strictly defined.

Selection of the vehicle
A vehicle is selected for the test. This vehicle needs to be eligible as the 'reference' vehicle for the 'family' it has to represent. There needs to be an agreement on a 'standard' colour for the body; preferably this colour should represent a kind of average in terms of absorption/radiation characteristics. In all other respects the reference vehicle needs to be the 'worst case' vehicle that falls within the vehicle definition of the vehicle family. The engine in this vehicle needs to be a representative engine, e.g. the best selling one within the range. Alternatively the engine could be chosen that will produce the worst case drive energy requirement for the compressor (see under STEP 2).

Preconditioning of the vehicle
The vehicle selected is placed in the climatic chamber, and is parked there for at least [2] hours under circumstances of standardised ambient temperature and humidity and standardised radiation:

- Temperature T_{amb} = 299 K (26 °C)
- Humidity = 60 % relative humidity at 26 °C (ca. 13 g of water per kg of dry air)
- 'Solar' radiation = 850 W/m^2

As an alternative to the requirement of a simulated solar radiation, a need for cold air may be determined without radiation, but in that case a default multiplier factor must be used for the equipment drive energy as determined in STEP 2. This multiplier needs to be set at a worst case value. If a manufacturer feels that he is put at a disadvantage with this default value, he has the option of determining the true influence by a real radiation of 850 $W/m^{2.}$ The exact value of this multiplier still has to be determined.

Testing of the reference vehicle

- After at least [2] hours the air-conditioner is switched on and run through a cycle of compressor speeds equivalent to those occurring in the fuel consumption test cycle. The most straightforward way of doing this is by starting the vehicle's engine and running the vehicle through the actual driving cycle (in which case suitable measures may be taken to avoid heating up of the climatic chamber through the engine's cooling system and exhaust), either on a pair of free turning rollers, or on an actual chassis dynamometer. Alternatively it may be done by means of a separate dedicated drive of the compressor and fans, installed for the purpose.
- As far as necessary the air-conditioner system will be initially adjusted for phase 1, the cooling down of the vehicle interior. The time needed to cool down the interior to the prescribed interior temperature will be checked. If the prescribed time is exceeded (or the prescribed temperature cannot be reached at all) the test will be regarded as invalid, unless the system has been running at full power and no other family member would be able to fulfil the requirement either (the "Panda option").
- As far as necessary after the cooling down phase the setting of the air-conditioner system may be readjusted for phase 2: maintaining the vehicle interior temperature at or below the stabilised prescribed interior temperature. This adjustment will be kept constant for the remainder of the test cycle. If the prescribed temperature is exceeded during this phase of the test, the test will be regarded as invalid.

Alternative options

The manufacturer will have two options for determining the fuel consumption effect of the air-conditioning system:

- Under OPTION 1 he may determine the fuel consumption directly during the test described above, and subtract the fuel consumption determined in a test without the air-conditioning system in operation. This latter test may have been executed on a standard chassis dynamometer in a standard (non-climatised) test chamber. This option is only available if the test in the climatic chamber did include the simulation of solar radiation.
- Under OPTION 2 he may determine the fuel consumption in a separate test, further described under STEP 2 and STEP 3.

Parent air conditioner system in reference vehicle: STEP 2

Under Option 2, STEP 2 determines the energy input needed to drive the air-conditioning system (under Option 1 this is not needed, since the extra fuel consumption resulting from the operation of the air-conditioning system is determined directly). Option 2 is needed in any case whenever the manufacturer desires to use the simplified method for subsequent members of the air-conditioning system family. If the test in the climatic chamber did not include the simulation of solar radiation, the drive energy so determined should be multiplied with the multiplier mentioned under the paragraph on preconditioning. This multiplier should represent a worst case condition.

Item to be measured for 'Option 2'
By means of a torque-measuring device in the compressor drive (usually a system with belt and pulleys) the speed dependent torque will be measured and converted into an overall energy consumption. In the case of an electrically driven compressor the necessary electrical energy is determined, in this case independent from the engine speed. The electrical power needed to drive the fans providing the air flow over the heat exchangers is also determined, either as a separate figure (in the case of a mechanically driven compressor) or as a figure to be added to the compressor drive energy (in the case of an electrically driven compressor). The final output figure of this step is the requirement of X kWh of mechanical energy and/or Y kWh of electrical energy over the total test cycle. The additional fuel consumption resulting from the engine needing to provide this drive energy consumption will be determined in STEP 3.

Additional items to be measured for Option 2, in the case of a family
In the case of a family of air-conditioning systems the drive energy consumption of each system may be determined directly, in the same way as for the parent, or an alternative approach may be followed. In this last case the following additional items shall be measured and determined:

- On the parent system the air-conditioner flow (Q) and the temperature drop of that flow (? t) will be measured. If the flow is partially reheated after the first cooling, the temperature drop will be determined by taking the difference between the ambient temperature in the climatic chamber and the system's final outlet temperature (i.e. after the reheating).
- The CFF (as defined below) will be determined and averaged over the cooling down phase (measurement values phase 1).
- Likewise the CFF will be determined and averaged over the stabilisation phase (measurement values phase 2).

The averaging of the flow and outlet temperature is done by determining for each phase of the cycle the 'cold flow factor' CFF, as follows:

$$CFF_{phase} = (Q * ?\,T)_{phase} = S\,(Q_{instant} * (T_{amb} - T_{outlet.instant}) * dt)\ [\,K\,.\,kg]$$

With:

$Q_{instant}$	=	the instantaneous flow of the A/C system in the relevant phase [kg/s]
T_{amb}	=	the standardised ambient temperature in the climatic chamber [K]
$T_{outlet.instant}$	=	the instantaneous outlet temperature of the A/C system in the relevant phase [K]
dt	=	the time interval over which the instantaneous measurement is made [s]

<u>Parent air conditioner system in reference vehicle: STEP 3</u>

When the fuel consumption of the operation has not been measured directly (Option 1), it shall be determined in the following way (Option 2):

- The engine of the reference vehicle is loaded with a simulated 'external' mechanical and/or electrical load equivalent to the load(s) determined under STEP 2.
- The additional fuel consumption due to this (these) external load(s) is measured.

NOTE: The industry has proposed to replace the necessity to measure the engine with a simulated external load by a calculation method. They offered to come with a proposal. The acceptability of this proposal as a possible alternative will have to be judged when it comes.

Additional item to be calculated for Option 2, in the case of a family
From the total mechanical and/or electrical load as measured under STEP 2 and the additional fuel consumption as determined under STEP 3 an average engine efficiency for the generation of this additional load shall be determined. This generation efficiency will be used for subsequent calculations for family members.

Airco system family members for the same vehicle family

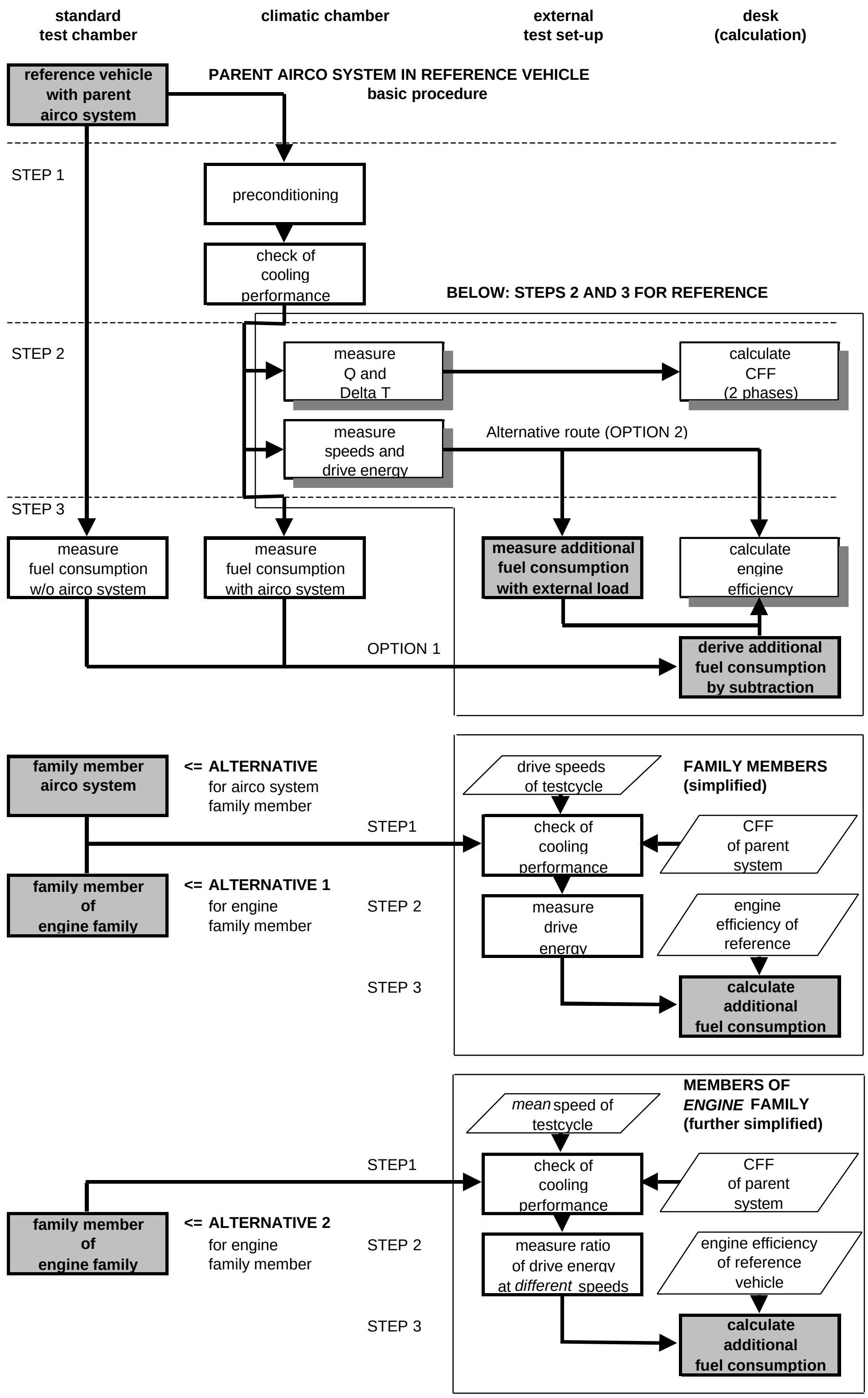
- Additional members of the air-conditioning system family may then be measured separately (on a dedicated test rig, outside the vehicle and independent of a climatic chamber). They should be driven in an appropriate way over a speed pattern equivalent to that in the vehicle in the case of the standard fuel consumption cycle. It should be checked that the CFF over both phases of the test is at least equal to that of the parent system. The temperature and humidity of the inlet air should be the same as that specified for the climatic chamber.
- By means of similar means as for the parent system the total drive energy consumption shall be measured.
- From this drive energy the additional fuel consumption should be calculated by using the engine efficiency as determined for the parent system in the reference vehicle.

Adaptation to different engines available for the vehicle family

The proposal as it was made above would apply to a pattern of characteristic compressor speeds for each installation that is available for that particular vehicle family, with that particular engine. The use of different engines within that family could result in different compressor speeds, however:
- The first possibility would be that, even with an engine that itself has different engine speeds over the driving cycle, the pulley ratio has been so adjusted that the compressor speeds are similar to that of the reference engine (margins further to be determined). In that case the drive energy would be the same, and no further adjustment of the additional fuel consumption is necessary.
- When for a different engine of the family the compressor speeds are different, the most straightforward way of dealing with that is to do the actual measuring with the engine that provides the worst case situation (presumably the combination that produces the highest compressor speeds) and to use that figure independent of the engine actually used.
- If the manufacturer desires to determine the actual system drive energy for the different engines available for the vehicle family, he can opt for the same procedure as was described above for different air-conditioning systems (alternative 1). This test needs only to be done for the worst case air-conditioning system layout, as it was identified in the tests with the reference engine.
- If the manufacturer wants to make use of an even further simplified procedure (alternative 2) he may determine the ratio in drive energy between the mean drive speed for the reference engine and that for the alternative engine, and apply this ratio to the overall drive energy as determined in the full test cycle with the

reference engine. It is suggested that this further simplified method is only applicable when the ‘correction’ ratio does not fall outside the interval limited by the values [1/1.5] and [1.5].

Figure 19: Flowchart: summary of the alternative testing possibilities



<u>The results relevant for the label</u>

The energy required to drive the air conditioning system has to be determined by the vehicle manufacturer for each air-conditioning system combination available on that vehicle family. A system is defined as a possible combination of a compressor, a condenser, an expander and an evaporator. The 'worst case' system combination (the one requiring the highest drive energy) is selected for the certification and labelling procedure. This is necessary, since the customer is not in a position to choose any particular combination; he has to accept whatever he happens to get. The result of this test will be X kWh of drive energy over the test cycle. The figure on the label will show an additional fuel consumption of x litre/100 km for the average operation of an air conditioning system available on that vehicle family (and possibly with that particular engine option). If so desired it could also have the dimension of y litre of fuel per hour of operation.

6.4 Auxiliary heaters

The methodology described can also be used for other auxiliary equipment that ultimately derives its mechanical or electrical energy from the vehicle's power source. The main example discussed here will be auxiliary heaters.

Auxiliary heaters can be classified as:
- Stand alone heaters, fuel fired by on-board fuel
- Electrically powered 'stand alone' heaters, externally powered
- Heaters powered by mechanical or electrical power derived from the vehicle's own power source.

Usually such heaters are either 'on' or 'off'. In any case a characteristic 'duty cycle' will have to be determined. In the simplest case such a duty cycle would only need to specify X time of operation after a cold start, and Y km of vehicle operation after a typical cold start.

STAND ALONE HEATERS

In the case of a fuel fired stand-alone heater it would be simple to measure the fuel consumed per cold start directly. This figure can be 'translated' into a CO_2-emission through the usual formula used to calculate a measured CO_2-emission into a fuel consumption (but then in reverse). The figure can then either be used for labelling in that format, or recalculated into an additional average fuel consumption per 100 km or per year, by taking the average trip length per cold start, or the average number of cold starts per annum, into account.

EXTERNALLY POWERED ELECTRICAL SYSTEMS.

In the case of externally powered electrical systems the characteristic electrical energy can be measured in the way that has been prescribed for the determination of the (external) electrical energy consumption of electrical cars. This can then be translated into CO_2-emission as for electrical cars, and expressed per cold start, per 100 km or per annum in the same way as for fuel fired heaters above.

HEATERS POWERED BY THE VEHICLE’S ON-BOARD POWER SOURCE

In the case of a system powered by the vehicles own on-board power source a procedure equivalent to that for the air conditioning systems can be used.

If the system would only operate full power for an automatically set length of time, the amount of mechanical and/or electrical energy absorbed can be determined straightaway. If the system is not necessarily operating full power, but has either an operating time or an operational load condition depending on a certain operational temperature (e.g. of the interior or of the engine’s coolant) being reached, a STEP 1 procedure as in the flowchart on page 53 is needed, where only the word ‘cooling’ needs to be replaced by ‘heating’. For the check of the ‘heating performance’ a minimum requirement needs to be specified, e.g. with the specification of a ‘way point’ as in the cooling case. It is proposed that the preconditioning is performed as for the type VI (-7 ºC test). STEP 2 and STEP 3 would be the full equivalent to those for the air conditioning system, with the term ‘airco system’ replaced by ‘heating system’ where applicable.

The procedure for family members can be performed fully in accordance with the procedures as shown in the flowchart for family members.

FOR ALL TYPES:

If the system, e.g. by heating the engine coolant, has a positive influence on the engine efficiency during the cold part of the test, it is proposed that:

- this additional effect is determined separately or additionally, and
- the fuel consumption in the type VI test is used for the baseline.

6.5 Other auxiliary equipment

In the case of other auxiliary equipment the same basic set-up of this procedure would still apply. The main item would be a fundamentally solid determination of a characteristic duty cycle and the format that is given. And although that can be a formidable task for certain types of equipment, once that has been performed the further procedure can be fully covered by the approach that is outlined in the flowchart on page 53 and its description.

7 Limitations of the study and recommendations

The approach to a test procedure as proposed above was elaborated in close contact with the Commission on the one hand, and the automotive industry on the other. An important starting point, requested by the Commission, was the desire to keep the procedure as simple as possible, so as not to burden the industry more than strictly necessary, but even so to guard the necessity to obtain test results that would be sufficiently meaningful for the purpose of the Commission, i.e. to provide the customer with meaningful information. The original expectation was that the resulting procedure would be sufficiently simple to execute in a standard automotive emission laboratory. For that reason it had been the intention of the consultant to test the proposed procedure in its own laboratory, so as to provide proof of the practicability of the proposal. In the course of the project it became clear, however, that a procedure that would be sufficiently meaningful, even in the most simplified form possible, would really need a test set-up that would exceed that of a standard emissions test laboratory. In particular the simulation of solar radiation, as requested by the Commission (on the basis of the first study results, that strongly pointed to the necessity of such an approach, see) tended to include the need for a climatic chamber with radiation and specialised (even if not extremely complicated) measuring tools.

In fact it was the industry itself that pointed to the necessity of making use of a climatic chamber. Additionally the approach that is proposed, to restrict the use of this climatic chamber to the 'parent' air conditioner system and to limit the testing of any subsequent system for the same vehicle body to a power consumption test in a non-climatised environment in combination with a calculation procedure, necessitates the use in STEP 2 of specialised test equipment, designed for the purpose.

Ultimately this excluded any possibility for the consultant to check this procedure on its own facilities, at least within the constraints (time and money) of the contract. In consultation with the client it was therefore decided to work out the procedure as well as possible and to rely either on the industry or on a separate project for its validation.

Such a validation would incorporate:
- A check on the practicability of the procedure in the laboratory.
- The exact definition of the requirements for the procedure.
- Insight in the value of parameters and the variability of the values in relation to surrounding conditions.
- Insight in the possibility to use defaults with the knowledge of the variability and the level (of importance) of the parameters.
- A calculation of the actual cost-effectiveness based on actual measured data.

8 Costs

For a calculation of the cost-effectiveness of a considered policy measure it is obviously necessary to establish the costs of that measure (e.g. in k?) on the one hand, and the effects (e.g. in Mton CO_2 avoided) on the other. A simple division would then result in a figure in k?/Mton CO_2.

In the case of the present study the **costs** would, in their most extensive form, consist of:
1. the costs of testing and certification (labour and facilities)
2. the costs of developing more advanced systems
3. the additional costs of these systems to the consumer, if any

The **effectiveness** could consist of the following elements:
1. the CO_2 avoided because the labelling would stimulate car buyers not to purchase a car with airco
2. the CO_2 avoided because the labelling would stimulate car drivers to make more selective use of their airco systems
3. the CO_2 avoided because the labelling would stimulate manufacturers to develop more efficient systems, and buyers to demand and buy them.

In the extreme case the cost could be modified with the savings to the consumer of the fuel consumption avoided, and the CO_2 avoided could be modified by the CO_2 generated by the testing and certification needed, as some parties have suggested. But in practical terms it seems preferable to draw the system boundaries somewhat closer and to avoid such marginal effects.

On the cost side estimates were made for the costs of testing for an assumed representative number of vehicle and system variants for a typical European manufacturer (item 1). The car and system manufacturers should have been a source for the costs mentioned under 2 and 3, but they were not in a position to contribute, so no incorporation of these items were possible.

On the effectiveness side the items 1 and 2 would necessitate a socio-economic study, which is clearly outside both the scope of this study and the competence of the present contractor. It is the feeling of the contractor, however, as an expert that is at least aware of trends in the automotive field, that the air conditioner as a piece of equipment is moving towards general public acceptance and that the chances that this trend will be significantly retarded by any kind of labelling seem to be rather remote. Moreover this would result in a cost/benefit study rather than a cost-effectiveness study, which in fact is a different kind of study. And then there is, of course, the consideration that the use of an airco system has a demonstrable safety aspect as well, which would make it difficult for any higher authority to actively discourage its use. So the best that labelling could obtain seems to be a trend towards more efficient systems and use. The input for this item, item 3, should have been provided again by the industry, but here again the manufacturers declared themselves unable to provide concrete data.

For these reasons the contractor has limited this part of the study to a comparison of the costs per possible variant approach and the costs per vehicle, based on the costs of testing. This serves to show that the proposed approach, although seemingly complicated, could save a considerable amount of cost over a more straightforward testing, whatever the final effectiveness. The ultimate benefits can only be established by an effect study once a labelling scheme is in actual operation.

The calculations

The test procedure as proposed in the Chapter 6 is subdivided into the check of three separate systems: the body, the engine and the air conditioner itself. The basic idea behind this approach is that vehicles, engines and air conditioning systems may be arranged into 'families' and that family members may then be checked in simplified (shortened) procedures. Full testing of each permutation would lead to a gigantic number of tests to be carried out for the type approval. This chapter on costs is trying to create a feeling for the cost savings of such an approach relative to the 'full test' option. For that reason it focuses on two specific situations:

1. Testing all possible combinations of body, engine and air conditioners on the currently used procedure for type approval testing, extended with the application of a climatic chamber and preconditioning especially for a higher temperature.
2. Testing the subsystems separately according to the proposed test procedure, allowing the individual results to be the input for the calculation of the fuel consumption of every possible combination of the three mentioned subsystems. The proposed procedure leaves certain options for the manufacturer to choose other paths for the testing (Chapter 6: option 1, 2 and the alternative for the sub system 'engine'). The costs for these options have been calculated as well.

The calculation of the costs for the two situations are based on the following items:

- The costs are calculated for one manufacturer.
- The coverage of the range of vehicles, for which the number of body and engine options per manufacturer is estimated, is limited to passenger cars.
- The manufacturer is assumed to have 10 body variants in its product range of passenger cars.
- The manufacturer is assumed to have 10 engine variants in its product range of passenger cars.
- On the basis of information received from the car industry it is assumed that 20 variations of air conditioner systems are possible.
- The proposed test procedure leaves the option for the manufacturer to choose only one or more 'worst case' air conditioner systems for the type approval test. For this calculation it is assumed that a manufacturer would prefer to test more than one of such systems; for example a manually controlled and an automatically controlled system. A manufacturer might want to differentiate even more for systems that strongly differ in capacity. Because the number of tests for the subsystem 'air conditioner' strongly influences the total costs, the results will be presented for the options: 1, 2 and 5 systems.
- For the alternative method of testing engine families it is assumed that this option would lead to a halving of the number of tests for the subsystem 'engine'.
- It is assumed that per car or subsystem 1 test suffices to acquire type approval. The costs are calculated for 1 (type approval) test per car or subsystem. A multiplication of tests would result in a proportional raise of the costs.
- For option 1 the reference test is the test without the use of the air conditioner; it is assumed that this test has to be carried out anyway for all engine families and some body families. Therefore the number of reference tests without an air conditioner is assumed to be half the total number of tests. This also accounts for scenario 1.
- An hour of labour is assumed to cost 100 Euro.

- Equipment is assumed to cost 400 Euro an hour; the amortisation of the chassis dynamometer, the climatic chamber, the C.V.S. and the analysis of the regulated gaseous exhaust gas components are all supposed to be included in this figure.
- In the calculation the costs are differentiated for several tasks within the procedure: preparation (installing the test equipment), preconditioning, measuring and calculation.

Table 8: Costs for the 2 scenario's including the costs for the options in scenario 2.

Costs [kEuro]	Nr. of A/C system family members		
Scenario	1	2	5
1	360	720	1800
2a (option 1)	360	720	1800
2b (option 2)	102	109	129
2c (alternative engine)	87	93	114

Scenario 1: Full test for each vehicle-engine-system combination

Scenario 2a: Each reference vehicle/parent system combination is tested twice (once with and once w/o the system in operation)

Scenario 2b: The determination of the fuel consumption of the reference vehicle with the system in operation is determined separately, outside the climatic chamber

Scenario 3: As 2b, but with the added option of a simplified test for engine variants

The results of the calculations clearly show the difference between scenario 1 and 2. That scenario 2a shows the same costs as in 1 is due to the fact that for both scenario's the same number of tests should be carried out: for this scenario all possible combinations of the family members of the 3 sub systems are tested with the air conditioner switched on in a climatic chamber and with the air conditioner switched off in order to determine the additional fuel consumption.

For the increase of air conditioner system variants the testing of all possible combinations in scenario 1 and 2a the costs increase proportional: in this scenario for each extra reference air conditioner system, tests are carried out on all body and engine variants again with this extra air conditioner system. In practice, however, the costs may increase less than proportional because different air conditioner systems may not have to be built in all body variants. For the other options (2b and 2c) the costs of extra air conditioner family members increase with the costs needed for the same number of extra reference tests for these family members.

Option 2c is the least expensive because for this option the number of engines to be tested may be reduced.

The results of this calculation also apply for the testing of auxiliary heaters when can be assumed that for auxiliary heaters more or less the same procedure is required.

In order to get an indication on the possible costs per vehicle a simplified calculation was made with the maximum (2a, option 1) and minimum costs (2c, alternative engine) from the table above. The assumption was made that a small car brand, for example offering exclusive cars, sells 10.000 passenger cars from a model range of 2 and a large car brand that sells 1.000.000 passenger cars from his model range of 10. Also the

assumption was made that the manufacturer wishes to test 2 A/C family members separately.
For the small car brand the expensive 2a scenario leads to costs of about 14 Euro per vehicle, while for the large car brand this scenario leads to 0.72 Euro per vehicle. The cheapest scenario 2c leads to 2 Euro for the small car brand and 0.09 Euro for the large car brand.

9 Conclusions and recommendations

Next to benefits on comfort and safety, the use of air conditioners and auxiliary heaters comes with a requirement for additional energy to operate them. This results in additional consumption of fuel and an additional emission of the greenhouse gas CO_2. As part of the underlying study the magnitude of these effects has been established at an average of 0.28 litre/100 km (7 g/km of CO_2) for Central Europe. For auxiliary heaters the fuel consumption and CO_2-emission are probably in the same order of magnitude or considerably lower, depending on the type of heater used. Based on these figures, the additional fuel consumption and CO_2-emission due to the use of these auxiliaries in relation to the average fuel consumption (6,7 litre/100 km) and CO_2-emission (164 g/km) of the current European car fleet is considered significant by the European Commission. With the fleets CO_2-emission probably dropping to 140 g/km in the next years (driven by the ACEA voluntary agreement), the use of auxiliaries not being taken into account, there is a defined need to control these negative effects on the environment. A way of enabling this control is addressing the emissions and fuel consumption due to the use of air conditioners and auxiliary heaters during type approval. By incorporating this into the type approval procedure the next items could be facilitated:

- The consumer’s right to know and awareness about the additional fuel consumption of his/her vehicle when using auxiliary equipment like air conditioners and heaters
- The possibility for the consumer to identify efficient systems by means of labelling vehicles and systems.
- Encouragement of the industry to develop and market efficient air conditioners and heater.

In order to facilitate the items mentioned above, this study evaluated, next to establishing the magnitude of the problem, the possibilities for integrating mobile air conditioners and auxiliary heaters in the type approval test for emission and fuel consumption of passenger cars (M1 vehicles).

The most straight forward approach in order to establish the environmental performance of any auxiliary system during type approval would be to perform the fuel consumption test twice: the first time with the auxiliary system switched off and the second time with the auxiliary system switched on under certain conditions. The subtraction of the results of the second and the first test gives the effect of the auxiliary system. This set-up however would lead to at least doubling the amount of test to type approve a vehicle. The financial- and timing implications of such a procedure however would have severe negative effects for the automotive industry.

Taking these implications into consideration, the contractor looked for intelligent options in order to decrease the amount of actual test work, without compromising the basic requires of the procedure. This lead to a set-up in which car types on the market are grouped into certain families, enabling one test set-up per family (instead of one test per type). The basis for this family building process has been similarities between vehicle types. These similarities on vehicle construction level have been split up in 3 groups (subsystems):

- Subsystem I: the power generation system
- Subsystem II: the air conditioner system
- Subsystem III: the vehicle body and its environment

By means of establishing typical parameters for each subsystem (within a certain family) in relation to certain environmental conditions while executing the type approval fuel consumption test on a “parent vehicle”, the actual amount of tests needed to address the topic under investigation can be reduced significantly. In order to live up to the basic requirement of the procedure to be able to rank systems (combinations of the three subsystems) based on their environmental performance, the testing in a climatic camber under stabilised conditions is required.

To this end a general, although still sufficiently detailed, *approach* for a measurement procedure was developed, but not a fully worked out procedure itself. It was finally agreed that this phase of the programme would result in a report that could serve as a solid basis for a discussion between the Commission and the stakeholders (i.e. the relevant industry and the Member States). The outcome of that process could then serve as the necessary input for the next phase: the detailed development of the actual procedure and its evaluation. This evaluation would contain:

- A check on the practicability of the procedure in the laboratory.
- The exact definition of the requirements for the procedure.
- Insight in the value of parameters and the variability of the values in relation to surrounding conditions.
- Insight in the possibility to use default values for certain parameters based on the knowledge of the variability and the level (of importance) of the parameters.
- A detailed calculation of the actual cost-effectiveness based on actual measured data in a more final procedure set-up. The additional costs for executing the procedure at this stage is roughly calculated between 0.09 and 14 Euro/vehicle sold, whereas the benefits could not be calculated within the framework of the underlying project because of the large influence of socio/economic parameters on the actual benefits.

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